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Climate Change Resilience and Public Education in Response to Hydrologic Extremes in Singapore

Chew-Hung Chang[1*] **and Kim N. Irvine**[1]

[1]*National Institute of Education, Nanyang Technological University, 1 Nanyang Walk, Singapore.*

Authors' contributions

This work was carried out in collaboration between all authors. Both authors came up with the conceptual approach to the issue and provided data from aspects of their work for the paper. Chew-Hung Chang provided the meteorological aspects of the data while Kim Irvine provided the hydrological data. Both authors read and approved the final manuscript.

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ABSTRACT

Aims: In February and March 2014, more than 300,000 households were affected by water rationing in Kuala Lumpur, Malaysia and the surrounding State of Selangor. Further south, reservoir levels in Singapore were dropping, prompting the government to raise the water conservation rhetoric, but falling short of implementing water rationing schemes. The region experienced a dry spell that was unprecedented in the last 30 years. Preparedness for storms has been the "talk of the town" since the 2001, 2006 and 2007 extreme high precipitation events in the southern parts of the peninsula and in Singapore resulted in costly flood damage. While resilience has been a concept used frequently in climate change adaptation, it is derived from ecology, where it refers to the capacity of the system to respond to a disturbance and resist the impact or recover from the damage of the disturbance. This paper examines the case of Singapore as an urban area in responding to a similar extreme hydrologic phenomenon by examining the climate change resilience of the small city-state, with a view to recommending some

**Corresponding author: Email: chewhung.chang@nie.edu.sg;*

considerations in designing climate change adaptation strategies.
Place of Study: Singapore and peninsular Malaysia.
Methodology: The paper reviews the rainfall extremes statistics covering the last 30 years for Singapore and then takes a hydrologic event-based case study approach to more closely examine the impact of record storms and the drought of March 2014 to discuss aspects of resilience that can serve as lessons for tropical cities in future adaptation to a climate-changing world.
Results: Extreme rainfall events have become more frequent in Singapore over the past 30 years, while February, 2014 was the driest February since 1869. February, 2014 also had the lowest recorded daily relative humidity at 74.5%. Tropical cyclones are not expected to hit Singapore because of its location near the equator, yet Typhoon Vamei made history by delivering 210 mm of rain on 27 December, 2001. Between 19 and 20 December, 2007 Singapore received 366 mm of rain and within the same week another storm deposited 140 mm of rain in a 24 hour period. While there were some environmental and health impacts related to the February 2014 drought, including low dissolved oxygen levels in water and a localized fish kill, as well as reports of greater human respiratory problems, Singapore was able to weather the drought by requesting voluntary conservation measures, prudent reservoir management, and increasing the output of NEWater and desalinized water. Recent extreme rainfall events have produced localized flooding, but Singapore has progressively pursued a program of improved drainage, stream naturalization, and implementation of Low Impact Development (LID) technology to reduce flood-prone areas from 3,200 ha in the 1970's to 36 ha today.
Conclusion: We do not suggest that all countries need to have NEWater or desalinated water to solve drought problems. We do suggest that in managing rainfall related hazards, droughts and extremes have been treated rather independently. Based on the case study of extremes presented for Singapore we propose the importance of establishing a three-step preparedness program for extremes that includes Preparation (vulnerability and risk identification, adaptive capacity building, and monitoring), Response (information dissemination and relief action), and Recovery.

Keywords: Singapore; climate change resiliency; drought; rainfall extreme; urban flooding; water resource planning.

1. BACKGROUND

There is spatial and temporal variation in how climate has changed in Southeast Asia, which is a region that spans more than 4,000,000 km² and is home to more than 600 million people. In particular, the variation in the changes of Southeast Asian precipitation event frequency, intensity and duration has been established in previous studies [1,2,3,4]. Any increase in atmospheric or ocean temperatures will impact the hydrological cycle as water moves through the earth-atmosphere system. The latest IPCC reports have affirmed yet again the increasing average global temperatures. Droughts and floods will be more severe and will occur more frequently and last longer, over many places. "There will be more rain at high latitudes, less rain in the dry subtropics, and uncertain but probably substantial changes in tropical areas" [5]. The IPCC Fourth Assessment Report (AR4) suggested differences in water availability between regions [6] that have caused storms and droughts to become more pronounced. Indeed, there has been an increased ratio of rainfall in the wet to the dry season between 1955 and 2005 for archipelago Southeast Asia [7]. In other words, there are more droughts during the dry season and more storms in the wet season in the recent decades.

Stern [5] has warned that any changes in precipitation patterns across Monsoon Asia would "severely affect" millions of lives. While countries may receive more water, much of this will arrive during the wet season bringing potential problems of flooding [8]. Further, this extra volume of water is useful for agriculture only if there is effective storage for use during the dry seasons [5]. Standard design practice for urban infrastructure assumes stationarity of the rainfall time series for analysis of event magnitude and frequency, but there has been a great deal of discussion recently about whether such assumptions are appropriate. Some [9] suggest that at this juncture, due to high uncertainty, there is no reason to abandon concepts of non-stationarity, while others [10] suggest extensions or correction factors to existing flood probability approaches that potentially would provide more reliable forecasts. A similar correction factor approach was developed by Dormuth [11] to update intensity-duration-frequency (IDF) curves for design work, rather than entirely updating the IDF curves. Hirsch [12] recommended that research related to climate change and water resources should follow two paths simultaneously, with one path using climate change models to drive hydrologic models (i.e. a linked model approach) and the other path being more extensive analysis of long term hydrologic records (i.e. an empirical approach). In the developed world, some long term hydrologic records exist, but such is not the case for most urban areas in developing countries. Most urban runoff studies that have examined climate change issues, to date, take some form of the linked model approach [e.g. 13,14,15,16] and with a few exceptions [e.g. 17,18,19] most work has focused on cities in temperate, developed countries. Tait et al. [20] looked at how a variety of drivers, including land use change, environmental legislation, energy and resource stress, and climate change might influence sewer system design and operation in the U.K. between 2020 and 2080. Using an example sewershed and increasing currently used synthetic design storms by a factor of between 1.2 and 1.4, modelled CSO volumes and surcharging were expected to increase by 2020. Hirschman et al. [21] did not undertake modeling exercises but provided practical examples of how existing "hard" stormwater management designs (e.g. bioretention cells, rainwater harvesting practices) and "soft" adaptive management strategies can be implemented to accommodate the uncertainties of climate change. Most of the studies reviewed above were carried out in areas expecting increasing rainfall volumes and intensities. It is important to recall, however, that there are areas throughout the world that are expected to become drier by 2080 (Food and Agriculture Organization (FAO), 2008) [22].

It has been suggested [e.g. 23,24,25,26] that droughts historically have received less attention with respect to prediction and planning because they are "fuzzy", "creeping" phenomena, difficult to define until one is experiencing them, often difficult to define the exact end, and in fact conceptually difficult to identify (i.e. is it a rainfall drought, a runoff drought, a crop drought?). A drought policy and National Drought Policy Commission have been in place in the U.S. since 1998 [24], but recent reviews have concluded, for example, that while most western states have drought plans, the scope and depth of the programs is uneven and few states conduct post-drought assessments [27]. At the local level Fu and Tang [28] found coordination and implementation strategies to address drought under most community comprehensive plans needed improvement. The European Union has a standard drought plan and Spain has implemented a drought indicator system [26]. Isler et al. [29] noted that Australia fcouses more on supply than demand side management to address drought, with the main innovation here being the introduction of large scale desalination, which they argue "…distracts from the need to build adaptive capacity and resilience into urban water systems through an integrated, whole-of-cycle approach."

While frequently climate change studies have focused on heavy precipitation events, with a view to understand how the impacts can be managed better, there clearly is a need to consider the extremes of wet and dry conditions, since drought also can have large economic, social, and environmental impacts. In the perceived water-rich equatorial region of Southeast Asia, Peninsular Malaysia and Singapore experienced a record dry spell in February-March 2014 and this raised some interesting questions for climate change researchers and policy makers. How different are precipitation patterns for the region as a result of climate change and what are the impacts on society? Are the societies in the region sufficiently prepared to manage these impacts? Are they resilient? This paper therefore sets out to begin addressing these questions by focusing on two case studies of severe storms and one case study of a dry spell which are used to illustrate the impacts of the precipitation changes. A conceptual critique of storm preparedness and drought resilience to answer the question of how are people in the region affected by extreme events is provided as a starting point to help direct attention and dialogue to the importance of learning to adapt to climate change in urban areas of Southeast Asia.

“Resiliency” refers to the ability of a system to respond and recover from disasters and includes attributes that allow the system to absorb impacts [30,31]. Many have noted that resiliency in fact may be a key ingredient of sustainability as well as vulnerability reduction, such that resilient systems (including biological and socio-economic systems) are able to survive, adapt and grow in the face of uncertainty and unforeseen disruptions [e.g. 30,31,32]. Fiksel [31] argued that a systems approach is necessary to better understand the linked behavior of complex social, economic, and biophysical systems so that we can improve our decision-making with respect to resilience and sustainability and provided a number of examples of complex, ongoing, modeling efforts, including thermodynamic life cycle analysis. While Sahely et al. [33] also noted the possible use of life cycle assessment as a method to evaluate sustainability, specifically for urban infrastructure systems, ultimately they used an indicator approach in their case study for the city of Toronto and there seems to be a groundswell of support for using such indicator approaches [e.g. 32, 34,35,36]. Our study takes a simpler, qualitative, case study approach to discuss resiliency as within the last 8 years we have been afforded clear examples of the extreme swing in events and it seems timely to use a case study approach given the record drought that was experienced in Singapore and Malaysia in 2014.

2. METHODS

2.1 Study Area

This paper focuses on Singapore, with some comparisons to its northern neighbor, Malaysia (Fig. 1). Singapore is a small island nation-state located at the southern end of the Malaysian peninsula. It has a total area of 715.8 km^2, with an east–west length of only 49 km and a north–south length of 25 km. At a current total population of 5.3 million (up from 1.6 million in 1960), Singapore’s population density of 7, 257 people/km^2 is ranked the third most dense in the world, after Macau and Monaco. Singapore’s per capita GDP in 2011 (adjusted for purchasing power parity and based on current international dollars) was higher, at $60,688 than either the United States ($48,112) or Canada ($40,370) according World Bank statistics [http://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD]. Land use characteristics in Singapore are well described by Ng [37], but an interesting aspect of Singapore’s fabric is that traditional housing essentially has vanished and more than 80% of the population lives in high-rise apartments as part of the Housing Development Board's estate plans.

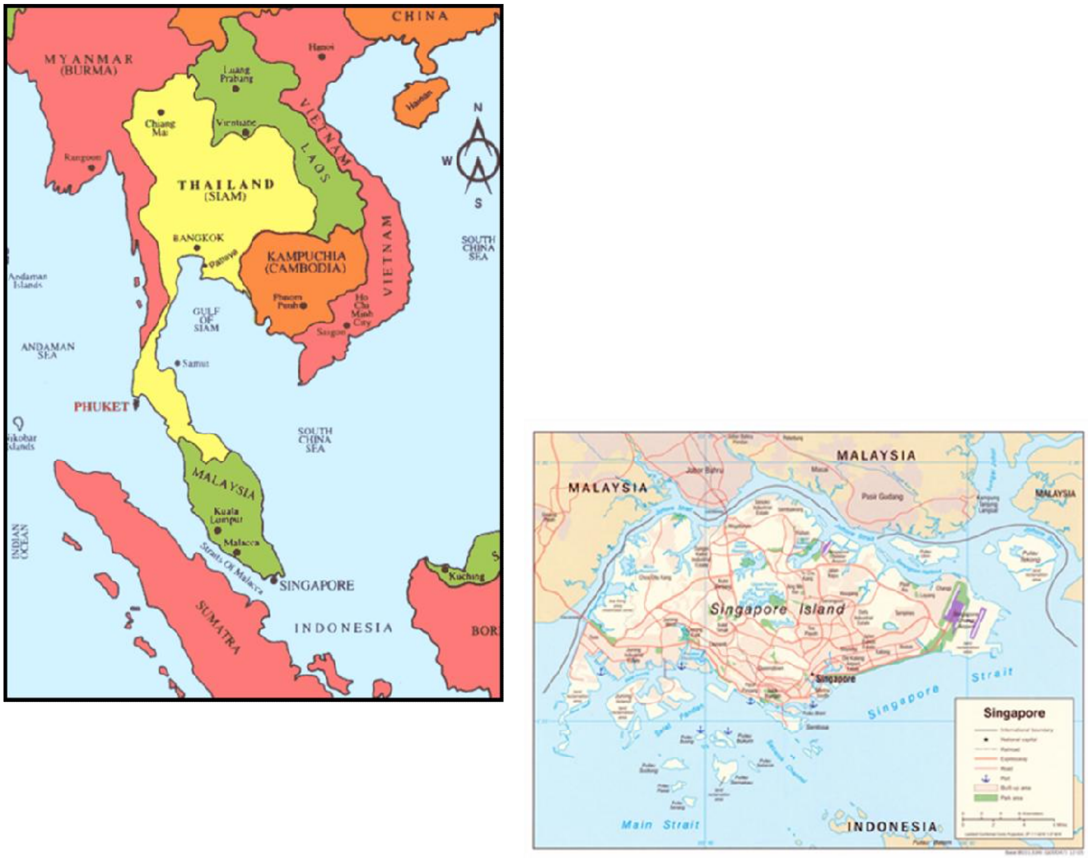

Fig. 1. Peninsular Malaysia and Singapore

The climate of Singapore is classified under the Koppen system as a tropical rainforest (Af) with no true dry season. Annual mean rainfall is approximately 2,343 mm and annual mean temperature is 27ºC. The annual maximum 60 min rainfall intensity, 1980–2010, ranged between 70 mm/h and 130 mm/h. In keeping with its tropical rainforest classification, the mean number of days/month with rain ranges between 11 and 19, and the minimum number of rain days per month is in the range 1 to 3 [http://app2.nea.gov.sg/weather_faq.aspx;http://app2.nea.gov.sg/weather_statistics.aspx].

2.2 Data Collection

This study used both primary and secondary data sources to explore the hydrologic extremes issue. First, a literature survey of various works on storms in Asia was done to determine the changes to precipitation patterns in the region and a trend series analysis of data collected for Singapore is presented to provide some preliminary empirics on the issue. The average monthly rainfall data from the Changi Meteorological Station, Changi International Airport (Fig. 1), 1984-2014, were used in the trend series analysis.

As part of an ongoing water quality study being conducted by the second author, YSI 6920 data sondes (YSI Inc., Yellow Springs, OH, http://www.ysi.com/index.php)have been deployed in a wet storm water detention pond that takes runoff from a park in northern Singapore and also serves as an ornamental water feature for a restaurant. The data sondes record dissolved oxygen, temperature, conductivity, pH, and turbidity at 15 minute time intervals. Data are downloaded on a weekly basis, and routine maintenance of the sondes is done at the same time. Most pertinent for this study (since we examine the relationship between drought and dissolved oxygen for ecosystem health), the dissolved oxygen sensors are calibrated weekly, using the 100% air saturation method recommended by the manufacturer. This calibration approach also has been used routinely in other field efforts and environments throughout the world [e.g. 38,39,40].

3. RESULTS AND DISCUSSION

3.1 Rainfall Pattern Changes Over the Last 30 Years

Lau and Wu [2] reported that the extreme high (top 10%) and low (bottom 5%) tropical rainfall events are becoming more frequent between 1979 and 2003. This is corroborated by research showing increasing variability in extreme dry and wet conditions of both the East Asian Summer monsoon and the Western North Pacific Summer monsoon [3,4,41,42]. A summary of the different types of changes to precipitation for the Southeast Asian region is included in Table 1. While there may not be consensus on the absolute intensity of precipitation events, there is general agreement on the increase in frequency of both extreme rainfall and drought periods.

Table 1. Changes in tropical precipitation in the recent decades

Works cited	Period of study	Study Area/Region	Frequency of low precipitation events	Frequency of extreme high precipitation events	Intensity of extreme events
Aldrain&Djamil, 2008 [7]	1955 - 2005	Java, Indonesia	Increase	Increase	Droughts and storms are more pronounced
Chen, Yen &Weng, 2000 [41]	1979 - 1993	East & Southeast Asia	Increase	Increase	Heavy rainfall events in Eastern China
Kharin et al. 2007 [1]	2046-2065 2081 - 2100	Tropical Pacific	-	Increase	-
Lau & Wu, 2007 [2]	1979 - 2003	Tropics	Increase	Increase	Total precipitation amount increased two folds from1980s to 1990s
Yim et al. 2008 [43]	1979 - 2005	East Asia and Southeast Asia	Increase	Increase	-
Zhou & Chan, 2005 [44]	1979 - 2001	South China Sea	Increase	Increase	-

(Source: Adapted from Chang [45])

Chang [45] reported an increase in extreme wet events in Southeast Asia based on the rainfall records from 10 stations from 1978 to 2008. The monthly precipitation from January 1978 to December 2007 was normalized for the 30-year average monthly precipitation and its standard deviation was used to analyze the extreme rainfall events. Normally 30-year rainfall for any area is collected for a calendar year but the period chosen in this study was from 1 May 1984 to 30 April 2014 so that the period covers the dry spell in Singapore in 2014, one of the case studies in this paper. Using an index developed by Chang [45], the values of $Z_{m,y}$ were calculated to represent the deviation from the distribution of monthly rainfall normalized by the mean rainfall of each month and its standard deviation. Higher $Z_{m,y}$ values indicate more extreme precipitation while values lower than -1 indicate extreme dry months.

$$z_{m,y} = \frac{p_{m,y} - \bar{p}_m}{S_m}$$

where,

$z_{m,y}$ = Normalized monthly precipitation for month $\boldsymbol{m}$ in year $\boldsymbol{y}$

$p_{m,y}$ = Precipitation for month $\boldsymbol{m}$ in year $\boldsymbol{y}$

$\bar{p}_m$ = Mean monthly precipitation for month $\boldsymbol{m}$ over a 30 year period

S_m = Standard deviation of monthly precipitation for month $\boldsymbol{m}$ over a 30 year period

Using updated rainfall records from 1984 to 2014, the index $Z_{m,y}$ was used to compare against the trend reported in Chang [45].

Based on the updated records for Singapore, there were more extreme wet events than extreme dry events in the last 30 years. Fig. 2 shows the normalized monthly rainfall for Singapore in the last 30 years. There were more months with rainfall higher than the 95th percentile of all monthly rainfall than the number of months below the 5th percentile of all monthly rainfall. In analyzing higher intensity events that could cause flooding damage, the PUB shows the annual frequency of occurrence of hourly rainfall total exceeding 70 mm to be about 8 days per year, which has been increasing at an average rate of 1.8 days per decade since 1980 (Fig. 3). These observations affirm findings from various studies in the literature about more frequent high precipitation events (Table 1). However, the tail end of Fig. 2 shows a noticeable dry event, which caught Singapore by surprise. It is this unexpected turn in precipitation trend and the adaptive ability in this small island state that has raised the issue of climate system resilience in this paper. In addition to a range of impacts that high precipitation events can bring, dry spells can also affect the economy and its people adversely. The following sections will outline the range of impacts that extreme precipitation events bring, with specific focus on three case studies. The authors are not implying that every single storm or dry spell is due to climate change, but rather use examples of existing extreme weather events to discuss how society can be more adaptable and resilient to changes in weather patterns that can be potentially brought about by climate change.

3.2 Two High-Precipitation Events

In any meteorology textbook, *Coriolis force* will be listed as a key ingredient for tropical cyclone formation. It has been considered theoretically improbable for cyclones to form near the equator. However Typhoon Vamei made history and challenged the common understanding of tropical cyclone formation as it made landfall in Singapore on 27 December 2001, hardly one and a half degrees north of the equator [47,48]. A persistent north-south pressure gradient across the equator created by a storm surge of extended duration over the South China Sea has been cited as the reason for this anomalous formation [49].

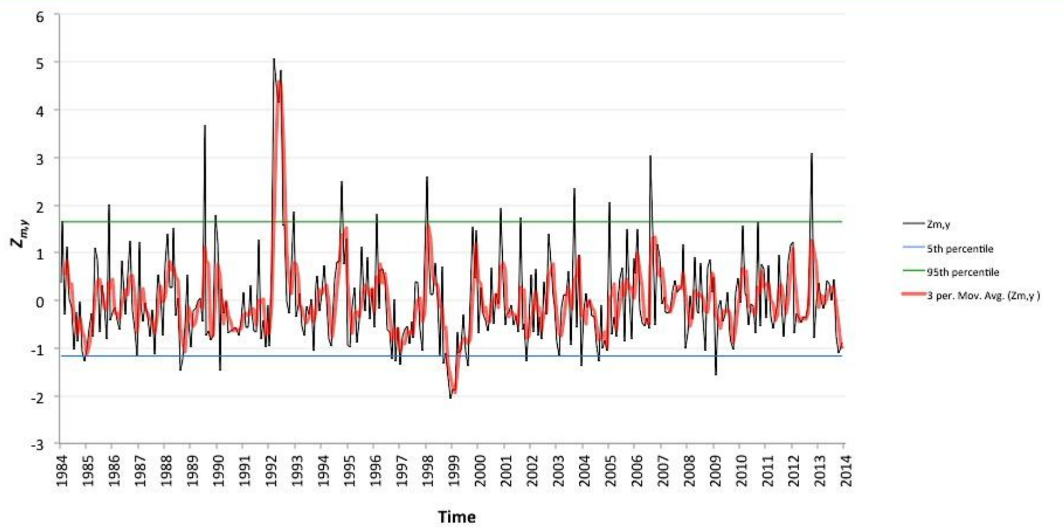

Fig. 2. Normalised average monthly rainfall recorded at Changi Meteorological Station, Singapore from 1984 to 2014.
Compiled from National Oceanic and Atmospheric Administration, n.d. [46]

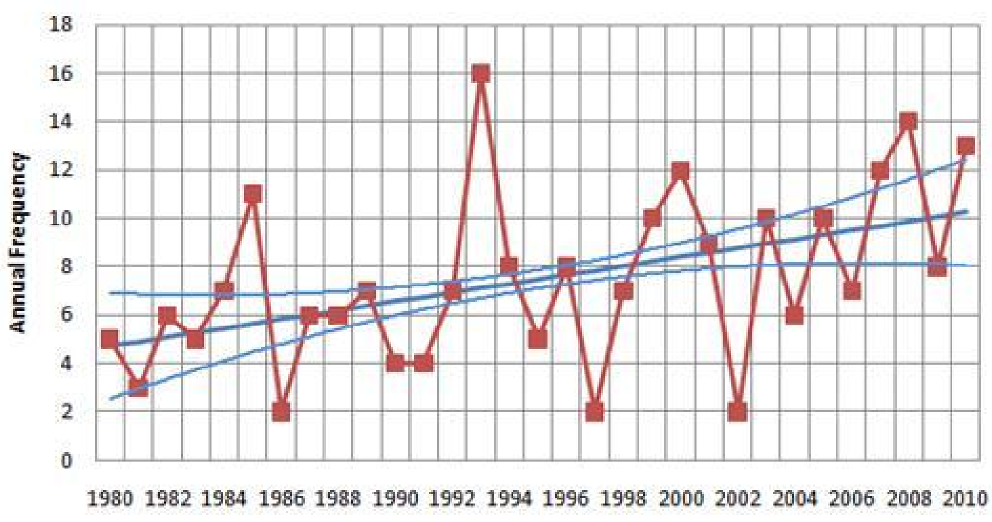

Fig. 3. Annual frequency of occurrence of hourly rainfall total exceeding 70 mm
[from http://www.pub.gov.sg/managingflashfloods/FMS/Pages/FloodResiliencePlan.aspx].

In the weeks leading up to the event, a low-pressure vortex was hovering over the South China Sea in an area with Borneo to the east and the Malay Peninsula and Sumatra to the west [50]. This vortex blocked the northeasterly monsoon winds and deflected the winds around the vortex, causing the winds to blow from a northwesterly direction. Coupled with the prevailing Northeast Monsoon winds and the northwesterly wind, these two prevailing bodies of air "wrapped around the vortex and the net result was a spinning up of a rapid counter-clockwise circulation that is similar to the spinning of a top played by a child; this led to the development of Typhoon Vamei" [49].

In Singapore, 240 mm of rain fell over a 24-hour period on 27 December 2001, which is equivalent to 10% of the entire 2001 rainfall amount. At Senai meteorological station in Johor, Malaysia, the recorded rainfall exceeded 210 mm on the same day. Further, heavy rainfall was received in the states of Johor, Kelantan, Terengganu and Pahang [50]. Fig. 4 illustrates this sudden increase in rainfall over a short period of time. As the average climatic rainfall for the month of December in the region is 225.5 mm, the rainfall within a single day when Vamei made landfall was equivalent to all the rain that is expected for the whole month. The anomalous amount of rainfall received resulted in flooding and mudslides in the Johor and Pahang States. More than 17,000 people were evacuated and there were 5 fatalities [51]. A landslide occurred at Gunung Pulai, destroyed four houses and killed five people. This event cost the Malaysian government an estimated 13.7 million Malaysian Ringgit ($4.3 million USD) damage to crops, education, transportation, and health-care facilities due to river flooding [52].

This key impact of the storm was not due to the typhoon itself but rather the lack of preparedness for such an unexpected event. One may argue that the storm was a theoretical impossibility until it happened, and people will not know what they do not know. However, the region experiences high rainfall during this time of the year annually and one could argue that flooding due to high rainfall must be something that the local government and people should be prepared for. Indeed, the lesson learnt from the storm event in 2001 should have been a warning sign, but ironically in December 2006, just a few years after Typhoon Vamei, floods once again hit Johor and this time the high rainfall event displaced no fewer than 200,000 people [53,54].

Between 17 to 20 and 24 to 28 December 2006 and from 11 to 14 January 2007 there were three occurrences of extreme high rainfall over South Johor and Singapore (see Fig. 5). These three events were due to the moisture brought in by strong northeasterly winds over the South China Sea [54]. The highest recorded rainfall of 366 mm occurred between 8 pm on 19 December 2006 and 8 pm on 20 December 2006. Within the same week, another storm brought 140 mm of rain in a 24 hour period on 26 December. In December 2006, a total of 765.9 mm of rain fell over Singapore, making it the highest ever recorded for December since 1869. Compounded with the 19-20 December storm, the events resulted in landslides, disrupted traffic, caused flooding, damaged buildings, uprooted trees and collapsed quarry walls, among other impacts [55]. The total economic loss was estimated at $500 million USD [54].

Floods are usually found in the northeastern parts of Peninsular Malaysia but not in the south during the Northeast Monsoon season. The government and people were unable to cope with the abnormally high levels of river discharge in this one in a hundred year flood. Interestingly, another flood of similar intensity and magnitude struck Johor less than three weeks later, but the rhetoric of another one hundred year flood "returning in a space of three weeks" quickly disappeared [53]. The key point about climate change resilience in these two case studies is that the lesson from Typhoon Vamei was not well learnt by the time the floods of December 2006 happened. Whether global warming is or is not a direct cause of the increase in frequency of extreme rainfall events, the fact that a theoretical impossibility was refuted had not helped the local and national governments, as well as the people cope better with subsequent storms. Given a more certain outlook in the literature on more erratic precipitation events, there is an urgent need to address the capacity of a society to adapt to changing weather patterns brought about by climate change.

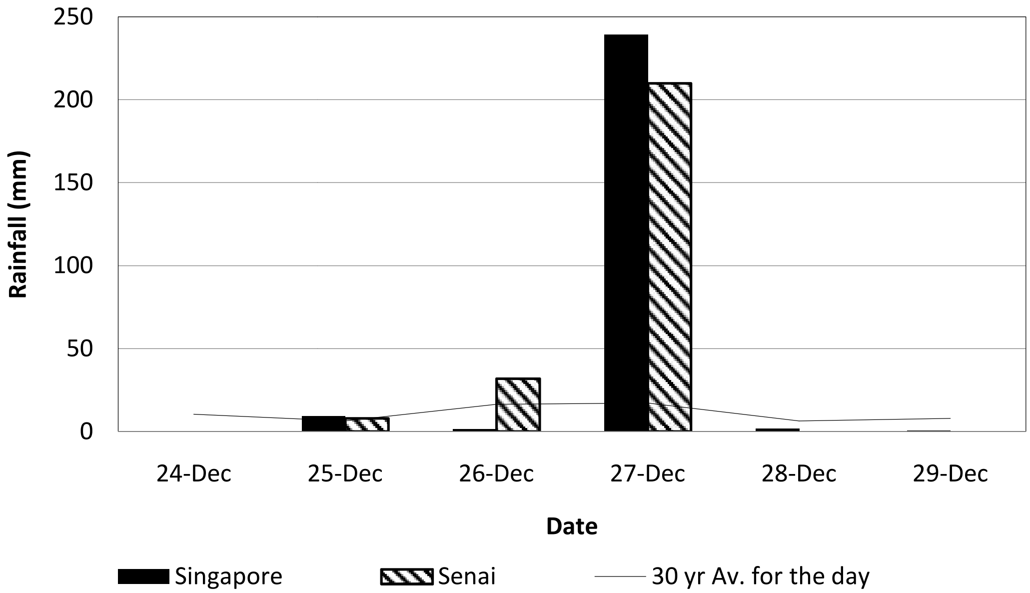

Fig. 4. Rainfall for South Johor and Singapore during Typhoon Vamei in 2001
Source: Adapted from Chang [45]

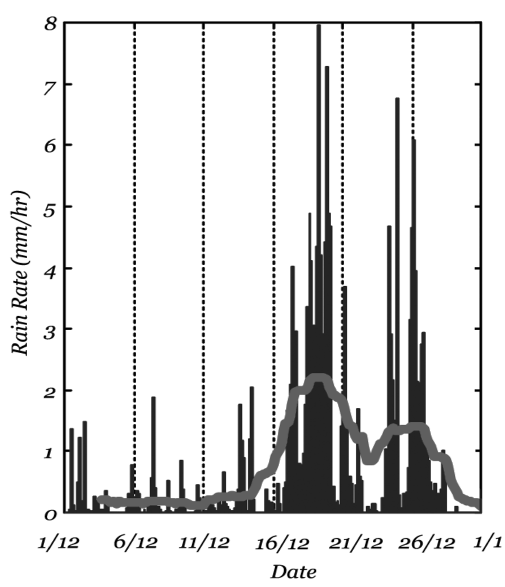

Fig. 5. Rainfall rate per hour over South Johor and Singapore
Note: Area-averaged (1°N–2.5°N, 102.5°E–105°E) precipitation rate (mm/hr) for December 2006. The thick grey line indicates the five-day running means (Adapted from Tangang et al. [54])

3.3 A Dry Spell

In the 61 days between 14 January to 16 March 2014, Singapore experienced an unusually dry period where the overall rainfall was 0.2 mm at the Changi Meteorological Station [46]. The National Environmental Agency (NEA) called it the driest February since 1869[56]. In February 2014, there were a very few scattered showers between February 7 and 19 over localized areas in the western part of the island. The total precipitation across all the rainfall stations monitored by the NEA ranged from 45 to 100 percent below the long-term average February rainfall of 161.0 mm [http://app2.nea.gov.sg/corporate-functions/newsroom/advisories/dry-spell-advisory-(4-mar) Fig. 6]. In fact, close to half the stations recorded less than 10 mm of rain for the entire month with the highest rainfall recorded being19.2 mm on 17 February at a station in the northwestern part of the island. The persistent dry conditions also resulted in the lowest recorded average daily relative humidity of 74.5 per cent for the month [56].

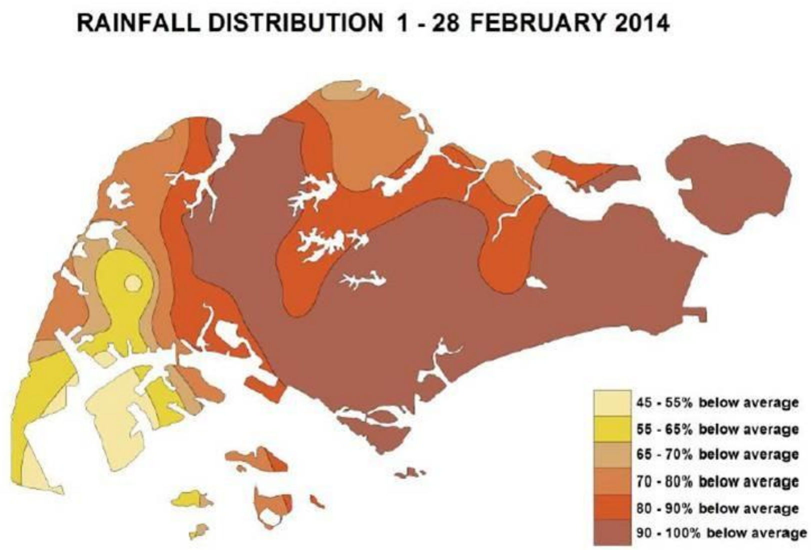

Fig. 6. Deviation from rainfall average for Singapore in February 2014
Source: National Environment Agency [http://app2.nea.gov.sg/corporate-functions/newsroom/advisories/dry-spell-advisory-(4-mar)]

While a dry period during the weakening phase of the Northeast Monsoon season is normal, what was abnormal was the extended duration of this dry spell [57,58]. Initial speculations by the authorities and local scholars point to possibly cooler than usual sea surface temperatures over the South China Sea which would have reduced evaporation and deprived the region of moisture that is needed to form rain [57]. Besides, the winds were still predominantly blowing from the northeast with average daily wind speeds of 13.3 km/h in February 2014, also coincidentally the windiest month in the last 30 years. With the combination of steady northeasterly winds and the cooler sea surface temperatures, a break in the monsoon winds by the middle of March or what is called the inter-monsoon period was expected to end the dry spell with the return of local convection rain [56]. Indeed, the heavy rains returned to Singapore on 16 March, attributed by the NEA to a tropical easterly disturbance, with the highest rainfall recorded in an hour being 33.2mm at Sentosa Island in the southern part of Singapore [59].

Of course, the key impact of the dry spell for Singapore was on the supply of potable water. However, other environmental and social impacts also were observed during this time. Apart from an evidently browning landscape, a single episode of mass death of fish at an offshore fish farm was recorded [58]. Fish kill episodes such as this periodically are observed in Singapore and have been attributed to warmer temperatures and low dissolved oxygen, as was the case in the Kallang River in June 2014 [http://www.straitstimes.com/breaking-news/singapore/story/hundreds-dead-fish-found-bishan-ang-mo-kio-park-river-20140205]. Water quality monitoring in a storm water detention pond during this drought period illustrates this potential impact clearly (Fig. 7). General practitioners saw about 20 to 30 percent more patients with colds, sore throats and cough symptoms during the dry spell [http://www.straitstimes.com/st/print/2111849].

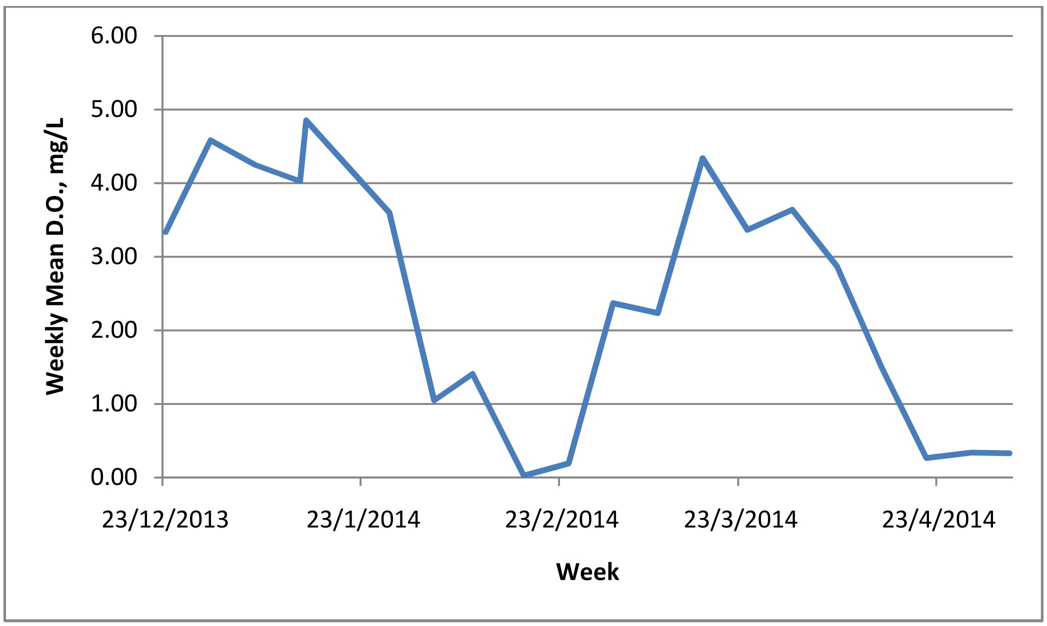

Fig. 7. Weekly mean dissolved oxygen (d.o.) levels near the outlet of a stormwater detention pond in Singapore

Weekly mean values were based on measurements recorded every 15 minutes with an YSI datasonde 6920. Low d.o. levels in April also occurred during a dry period, but it was not as severe as the February drought. Rainfall recorded at the tipping bucket gauge adjacent to the pond was: 16 March – 28.8 mm; 17 March – 34.4 mm; 18 March – 24 mm; and 19 March – 29.6 mm.

The dry spell also affected Malaysia where water levels in reservoirs dropped below 50% in Selangor, the country's most populous state, resulting in the implementation of water rationing. In peninsular Malaysia, 15 areas did not experience rainfall for more than 20 days [58]. The state of Negeri Sembilan, just south of Kuala Lumpur, even had to declare a "state of crisis" on 26 January 2014 [60]. Consequently the Malaysian government imposed water rationing on 300,000 households in the Federal Capital of Kuala Lumpur and the adjacent state of Selangor, as well as another 50,000 households in Southern Johor [61]. Apart from water rationing, the dry spell was blamed for forest fires, dengue fever outbreak as well as lower agricultural productivity [58,61].

The irony is that part of Singapore's water supply comes from buying treated water sold by Malaysia. Despite this dependence on imported water from her neighbour, Singapore did not have to resort to water rationing. Indeed, the environment ministry assured the public during the dry spell that 55 per cent of the country's demand could be met by the water produced at the country's own desalination and used-water (NEWater) treatment plants "regardless of the amount of rainfall", which affords Singapore "a safety margin" [http://www.straitstimes.com/breaking-news/singapore/story/singapore-will-be-alrightdespite-dry-spell-conserve-water-vivian-bala]. Despite this safety margin, the National Environment Agency issued a dry spell advisory which encouraged the public to adopt water conservation measures. The national water agency, called the Public Utilities Board (PUB) sent circulars to 25,000 non-domestic customers advising on water conservation measures by 8 March 2014 [http://app2.nea.gov.sg/corporate-functions/newsroom/advisories/dry-spell-advisory-(4-mar)]. Nevertheless, the city-state was able to cope with the dry spell coming through relatively unscathed and demonstrates what the authors would describe as resilience to climate change. By discussing how Singapore has managed the three historical wet and dry events, the authors will critically examine resilience within the large concept of climate change adaptation.

3.4 Preparedness and Resilience in Storm and Drought Events

The last time Singapore was as dry as February 2014 was in 1869, a good century and a half ago. Typhoon Vamei was probably a one in four hundred year storm [49] and the high rainfall event in December 2006 was a one in a hundred year storm. Although the chances that such extreme events will occur again in the immediate future are low, the cases described in this paper point to a need to be prepared and resilient for these unexpected occurrences. Many different analytical approaches and assessment frameworks have been proposed to help communities plan and prepare for climate change and associated greater extreme events, including use of indicators, input-output modeling, life cycle assessment modeling, and stochastic, risk-based simulations [e.g. 32,33,62,63]. To the extreme, Susskind [64] describes an interesting planning approach that included joint fact finding, scenario planning, and role play simulation. A pilot role play simulation, alone, took a study team 8 months to prepare and subsequently involved"…150communityleaders (including local and county elected and appointed officials, farmers, real estate developers, state legislators, environmental group heads, religious leaders, chamber of commerce members, fisherman, boating interests, and others)…" in Annapolis, Maryland. The effort also required guidance from 20 professional mediators during the 90 minute role playing exercise. While definitely interesting and inclusive, the planning exercise described by Susskind [64] points out the gap between developed and developing countries. Although we believe it unlikely that the developing countries of Southeast Asia would have the capacity to undertake this level of planning, Francisco [65] did note an example of four communes and eight villages in Thua Thien Hue Province, Vietnam, that used a scenario-building and participatory planning approach to implement climate change adaptation measures including construction of an inter-commune road and a multipurpose school to be used as an emergency shelter.

Rather than take one of the more advanced analytical and planning approaches here, instead we propose a simple framework for an adaptation program that fits and explains the Singapore context. As we will see, there is not a one size fits all solution, with respect to resiliency and water resource planning, and in fact the approaches will vary spatially and by political scale (i.e. country to country; federal to regional to local government). We propose the following key phases and steps to developing a useful preparedness program as an adaptation strategy:

1. Preparation
   a. Identify vulnerabilities and risks
   b. Adaptive capacity building (e.g. improve drainage systems)
   c. Monitoring
   d. Education and public outreach
2. Response
   a. Information dissemination (e.g. effective communication of warning and advisories)
   b. Relief action (e.g. evacuation)
3. Recovery
   a. Post-event recovery

These phases and steps in the Singaporean context are discussed in detail in the following paragraphs.

3.5 Preparation

3.5.1 Identify vulnerabilities and risks

Singapore has been lauded as a "model city for water management" and an "emerging global hydrohub" [66,67]. Luan [68] noted that the Singaporean government established legislation that goes hand-in-hand with a well-coordinated institutional framework to provide an integrated "whole-of-government" approach to land use planning, water management, a sound built environment and pollution control. Sanchez-Rodriguez [69] identified key ingredients for large U.S. cities that have been progressive in developing climate change adaptation measures include political leadership and central coordination of adaptation strategies. These characteristics certainly are true for Singapore and are discussed in more detail by Irvine et al. [70].

From the early years of independence, Singapore has had to deal with problems of droughts, flooding, serious water pollution and more importantly a lack of physical space to collect water. Singapore is barely 716.1 km^2 in size [71] with hardly any big rivers. There is also hardly any groundwater due to its geology [67]. Looking for other sources of water has become a matter of non-traditional security and has driven the country to identify the vulnerabilities, risks, and come up with alternative management and technology options. Singapore and Malaysia have a long history of water import agreements that stretches back to 1927. In 1961 and 1962, Singapore signed two water agreements with the state of Johor in Malaysia that allowed up to 86 million gallons per day (mgd)(390,963 cubic meters per day) and 250 mgd (1,136,520 cubic meters per day) of water to be purchased at the price of at 0.03 Malaysian Ringgit ($0.009 USD) for every 1,000 gallons up till the year 2011 and 2060, respectively [http://www.time.com/time/magazine/article/0,9171,1921608,00.html]. A new round of water negotiations began in 1998, which was linked to economic packages focusing on recovery from the Asian financial crisis. By 2003, Singapore had begun to look seriously for alternative water sources, including importing from Indonesia, and ultimately the negotiations with Malaysia ended without agreement [72]. With the expiry date of 2060 for the second agreement approaching, this has become the *de facto* planning horizon for Singapore to advance and diversify its technologies as it moves towards the goal of water self-sufficiency. Singapore began to look for alternatives to increase its water supply in the 1990s, largely out of security concerns, resulting in the creation of a "robust, effective and cost-efficient" way to meet Singapore's water needs - better known as the 'Four National Taps'. These four national taps include imported water, water from local catchments, intensely purified reclaimed water through used-water treatment known as ‘NEWater’, and desalinated water [67].

Apart from the natural catchment areas found in the center and western parts of the island, Singapore collects urban runoff from a network of “drains, canals, rivers, water collection ponds and reservoirs before it is treated for drinking” [73]. Singapore has progressively increased the area for water catchment from half to two-thirds of its land surface with the completion of the fifteenth to seventeenth fresh water reservoirs, namely the Marina, Punggol and Serangoon Reservoirs. A remarkable man-made reservoir, Marina Reservoir is the brainchild of the then Prime Minister of Singapore, Mr Lee Kuan Yew more than 20 years ago. With the construction of the Marina Barrage, a fresh water reservoir was formed out of the Marina Bay, which was previously open to the sea. The barrage collects runoff from a 10,000 ha area having a population of around 1,000,000 people [74] and also acts as a tidal barrier against possible inundation during high spring tides. In addition, the constant level of water maintained by the barrage has allowed water-based activities to be available right in the heart of the city [73]. The PUB intends to capture water from remaining streams near the shoreline, which will increase Singapore’s water catchment area to 90% by 2060 [http://www.pub.gov.sg/water/Pages/LocalCatchment.aspx; 74].

NEWater, as its name implies provides a new life to “used” water. An acclaimed pillar of Singapore’s water sustainability success [67,73,75,76], NEWater refers to the high quality reclaimed water produced from treated used water that is further purified through microfiltration, reverse osmosis, and ultraviolet disinfection. Since 2010, NEWater has been able to meet 30% of Singapore’s water needs. There are plans to expand this capacity so that NEWater can meet up to 55% of future water demand. Another innovation in seeking alternatives to Singapore’s water supply is desalinated water. Once considered a costly last option for water scarce countries, desalination technology has advanced dramatically over the past decade [77,78,79].Singapore’s first seawater reverse-osmosis plant produces 136,000 cubic meters of water a day. A second and larger desalination plant with a capacity of 318,500 cubic meters of desalinated water per day, was opened in September 2013. Together, desalinated water can meet up to 25% of Singapore’s current demand [73]. The plan is to ensure that the desalinated water sources are able to sustain 25-30% of the needs in the longer term [67,73].

The Singapore Ministry of Environment and Water Resources established an Expert Panel on Drainage Design and Flood Protection (EPDDFP) measures in 2011. This panel, consisting of local and international academics and consulting engineers, concluded that the PUB had done considerable good work on flooding issues over the past 30-40 years, but also made recommendations with respect to risk assessment, adaptive capacity, and education. Several of the recommendations will be noted in the following sections, but to begin, EPDDFP [80] recommended that “Singapore now needs to move towards a more integrated risk-based approach based on dynamic modelling and comprehensive monitoring” of its water resources. The PUB has begun to more fully develop its dynamic modelling capabilities both for runoff and reservoir management. The risk-based approach would consider the probability of flooding as well as the consequences of flooding (both tangible and intangible impacts). The EPDDFP [80] also recommended that PUB begin to “plan for the potential consequences of global megatrends and ensure that long term drainage solutions do not compromise Singapore’s capacity to respond to their impacts.”

3.5.2 Adaptive capacity building – the case of low impact development and drainage improvement

The use of stormwater runoff as a water source creates a balancing act for Singapore. The country wants to capture the maximum runoff practical, but also needs to balance the capture with concerns about localized flooding and quality of the runoff. One approach that increasingly has been implemented worldwide for stormwater quantity and quality management [cf. 81,82,83,84,85,86,87] and has been aggressively pursued in Singapore [70] is implementation of Low Impact Development (LID) technology.LID technology includes green roofs, rain gardens, rain planters, grassed swales, constructed wetlands, rain barrels, and pervious pavement. The intent is to manage rainfall at the source using uniformly distributed decentralized micro-scale controls. The LID goal is to mimic a site's predevelopment hydrology using design techniques that infiltrate, filter, store, evaporate, and detain runoff close to its source [http://www.lid-stormwater.net/background.htm]. LID addresses stormwater through small, cost-effective landscape features located at the lot level and therefore makes the system more resilient in that it does not rely on large, centralized control structures. Modeling efforts that assess the effects of these technologies increasingly are available, to the point that they are now explicitly included as an option in the Stormwater Management Model [88].

However, some important gaps in our understanding of LID operations remain, as, for example, there seems to be very little empirical data at a large sewershed scale, across multiple storms and seasons, to confirm performance of the technologies and models [89]. Modeling efforts to date seem to suggest that LID technologies are less helpful in managing larger events [90,91], although an unpublished report by Drexel University for a test area in Cambria Heights, New York City, showed that LID technology performed exceedingly well in controlling runoff from Super Storm Sandy and Hurricane Irene. Hopefully, the data gaps are starting to change with projects described, for example, by [92], although more work in tropical environments is needed.

Adapting to qualitative changes in climate and climatic and environmental transitions refers to transforming existing systems to ensure that development is viable and sustainable under future climatic uncertainty and the possibility of new climate hazards. This requires transformational change that occurs at a system level, such as by relocating activities away from flood prone zones [93].

Finally, other preparation activities undertaken by the PUB for extreme rainfall events include efforts to reduce localized flooding through a program of ongoing drainage improvement from about 3,200 hectares in the 1970s to 36 hectares today (Fig. 8).

3.5.3 Monitoring

The National Environment Agency's Meteorological Services Singapore (NEA MSS) currently monitors rainfall at 93 sites using real time automatic weather stations. Prior to the 1970s network coverage in Singapore was quite limited, and between 2012 and 2013, 31 of the 93 stations were added [80]. Rain gauge density in Singapore, as of 2013, is one gauge per 7.7 km^2, which well exceeds the density recommended by WMO [94] for urban areas at one gauge per 10-20km^2. The PUB maintains a network of 166 water level sensors in drainage canals and rivers around Singapore that update every 10 minutes and more than 40 of these sites also have CCTVs to visualize the site [http://www.pub.gov.sg/managingflashfloods/WLS/Pages/WaterLevelSensors.aspx]. The storm water level sensor data can be used to monitor flood potential in real time as well as to help optimize reservoir management for flood control and to determine how the production of NEWater and desalinated water need to be increased to meet the needs during a dry period. The monitoring system that now is in place is consistent with the recommendations made by the EPDDFP [80].

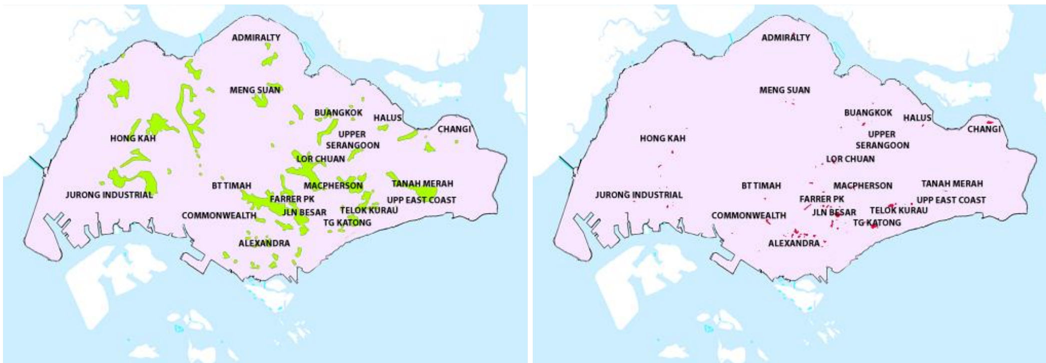

Fig.8. Flood-prone areas of Singapore in the 1970's (left) and now (right)
[fromhttp://www.pub.gov.sg/managingflashfloods/Pages/PastPresent.aspx].

3.5.4 Education and public outreach

Typhoon Yolanda (Haiyan) made landfall on 8 November 2013 as one of the strongest tropical cyclones ever recorded [95], killing at least 6,268 people in the Philippines [96]. The strong winds and heavy rains were accompanied by storm surges that measured at least 5 meters in height, destroying buildings including the Tacloban Airport terminal[97]. While countries in the western tropical Pacific are not unfamiliar with the heavy rains and winds of typhoons, the concept of a storm surge was largely unknown to many people in the Philippines as there is no equivalent word that would convey the dangers of a storm surge in the Tagalog language [98]. This vocabulary issue was used as an explanation for why people did not evacuate from the coastal areas even though the authorities had warned of 5 meter storm surges [99]. With this issue raised, it is hoped that public education can bring about greater awareness of the phenomenon and mitigate future life loss when a similar phenomenon occurs. This is perhaps only one facet that could shed light on how communities can be better prepared for storms. There are countless other examples of people and places impacted badly by storms, even when they occur on a yearly basis. Much can be learned from these lessons. Using the example from Hurricane Katrina, which also had a high death toll and displaced countless individuals, a good quarter of the people ignored evacuation orders even though ample warning was given [100]. In the case of Typhoon Vamei and the storms of December 2006, both events came as a surprise, which was largely due to a lack of preparedness. Perhaps this absence of preparedness can be explained by the prevailing political and scientific discourses on climate change in 2001. The IPCC Third Assessment Report (TAR) was unable to communicate its prediction of the impact of global warming as certainly as the Fourth Assessment Report (AR4) did. By 2007, the AR4 was "virtually certain" of the changes to precipitation patterns. There is little reason now for countries not to be prepared for heavy precipitation events such as Vamei-like storms, since there is general consensus in the literature that high precipitation events will occur more frequently.

Singapore which places high emphasis on climate change adaption and efficient drainage nonetheless was caught off guard in the 2010 Orchard Road floods. As the main shopping and tourist belt in the central business district, Orchard Road was inundated when 100 mm of rain fell within 2 hours, coupled with the fact that one of the canals serving the area was choked by rubbish and leaf litter [101]. In fact, the extensive greenery in Singapore promoted under the Garden City philosophy [102] poses some considerable risk to localized flooding due to clogged road inlets. These examples only go to show that there is still much more room for improvement in preparing for a more stormy and climate changed world. Following the 2010 (and 2011) flood events, the EPDDFP [80] noted that the PUB adopted a more proactive approach to sharing and communicating flood information, including the use of flood updates on radio, Facebook, twitter, and the PUB website. Yet, the EPDDFP [80] also noted that public preparedness might be enhanced through greater public engagement (e.g. through input to comprehensive flood response and recovery plans, or crowd-sourced reporting of flood locations).

Tortajada and Joshi [103] observed that the Singaporean school curriculum has played a central role in educating future generations with respect to water and the environment. For example, in 1987 a water conservation course was introduced at the secondary level to explain Singapore's water challenges and the importance of conservation. The PUB's Active, Beautiful, Clean, (ABC) Programme was initiated in 2006 to reconnect Singapore's population to its water. One of the signature components of the ABC Programme is the Waters Learning Trails which seek to provide unique, field-based learning experiences both for the general public and schools. To enhance the educational experience for schools, the PUB has keyed Learning Trails topics and information to the curriculum, with a multidisciplinary focus on the lower secondary level [http://www.abcwaterslearningtrails.sg/web/faq.php]. There are 11 Learning Trails located throughout Singapore, each with its own individual characteristics and opportunities and the PUB very much encourages teachers to get their students into the field and explore Singapore's water environment. The PUB also seeks to educate the public and schools about water conservation through their website [http://www.pub.gov.sg/conserve/WACProgramme/Pages/default.aspx].

3.6 Response

The common adage of saving for a rainy day needs to be reconsidered in the case of how Singapore responded to the dry spell of 2014 by saving water for a dry day. In fact, Biswas [104] argued that recent localized flooding events in Singapore have produced an unbalanced public dialog about water. He suggests that Singapore should be more concerned about droughts rather than floods and calls for the preparation of a comprehensive plan that would allow the island to withstand a prolonged drought.

Interestingly, while Malaysia responded to the 2014 dry spell by initiating water rationing to parts of Johor, Negiri Sembilan, Selangor and the Federal territory of Kuala Lumpur, Singapore adapted rather differently. There was hardly any restriction on the supply of water except for the few government advisories posted on the National Environment Agency website [http://app2.nea.gov.sg/corporate-functions/newsroom/advisories/dry-spell-advisory-(4-mar)].The most widespread impact of the dry spell was perhaps manifested in the trivial posting by netizens on the need to drink more water due to the lower relative humidity. There was a reported 20 percent rise in sales of cold drinks during the month of February [58].

Singapore has evidently developed sufficient resilience in responding to the onset of a dry spell, one hydrologic extreme event in the range of possible changes to the weather patterns due to climate change. Whether it is due to a reflexive response to the constraints that the tiny city-state faced due to the initial water supply conditions, or if it was part of a larger sustainability blue-print which the city has tacitly been implementing, the key features in the storm resilience concept that have been discussed above can be seen in this dry spell event as well.

In preparing for the inevitable shortage of water once the water agreements expire in 2011 and 2060, Singapore started planning its expansion of natural and urban catchment areas. The development of 17 fresh water reservoirs, the introduction of NEWater and desalinated water all were key ingredients to ensuring a sustainable supply of water for a future date. Coincidentally, the dry spell occurred after the completion of the second desalination plant in September 2013. This increased the capacity of desalinated water from 10 to 25% [73]. Had the dry spell occurred earlier, the outcome might have been different.

The response strategies observed during the 2014 drought episode were largely in terms of dissemination of information and providing an advisory to voluntarily mange the water demand. In addition to the advisories, the PUB dedicates a section of its website to "Water Reduction Measures During Dry Spells" [http://www.pub.gov.sg/conserve/WaterReductionMeasures/Pages/default.aspx#sthash.pFqIQA9H.dpuf]that provides information on conservation measures primarily for the domestic, commercial, and landscape maintenance sectors. Furthermore, in 2010, PUB introduced the Water Efficiency Management Plan (WEMP) program as a voluntary initiative to help non-domestic users better manage and conserve water. The WEMP involves development of a water balance chart to help identify areas for improved water conservation and establishment of an action plan which identifies measures in water savings, priorities and implementation timelines. Starting in 2015, it will be mandatory for all large water users (water consumption ≥ 5,000 m^3/month) to install water meters at the major water use areas in the facility and submit their WEMPs to the PUB on an annual basis [http://www.pub.gov.sg/conserve/WEMP/Pages/default.aspx].

3.7 Recovery

Once the rains returned to Singapore in March, 2014, it was business as usual [59] and as there was not much impact on the water supply, there was hardly any recovery work that needed to be done.

In examining the steps taken by Singapore in responding to the dry spell of 2014, it is evident that the key phases of preparing for and responding to the hydrologic hazard were in place to ensure that the city-state remained resilient to the dry spell. Given the similarity in the concepts of adapting to high precipitation events, there is scope to explore a common framework in planning the steps to take in ensuring climate change resilience to changing precipitation patterns.

Mitchell and Tanner [105] suggested that individuals, groups and natural systems should prepare for and respond to changes in climate or their environment, as a holistic approach to climate change adaptation by distinguishing risk factors between "hazard" (in terms of geographical location, intensity and probability) and "vulnerability" (in terms of susceptibilities and capacities) [105]. Further, the storm-related risk any society is subjected to is dependent on the social-cultural conditions of the people and the biophysical risks in the geographical region. Brooks, Adger and Kelly [106] proposed that an assessment of storm risk, the building of adaptive capacity and the actual adaptation strategies must be included when designing a storm preparedness program. Moreover, 3 main types of climate change adaption can be considered [93]. Policy makers and planners can endeavor to address the adaptation deficit by increasing the capacity of communities to cope with and recover from the impact of existing climate variability. Secondly, societies can adapt to incremental changes in existing climate related risks by increasing the capacity of communities to cope with extremes and variability in order to accommodate increased variability and more frequent and severe extremes, such as by climate proofing the drainage network in anticipation of more intense rainfall. Brooks et al. [93] propose that the success of any adaptation should be evaluated for its feasibility of implementation, efficiency, efficacy, and legitimacy with stakeholders, equity and sustainability of the program. However, these frameworks often provide extended discourse on the issue without outlining clear steps to operationalize the framework.

While being prepared requires an intimate understanding of the risks and vulnerabilities of a community within its geographical context [32], the adaptation strategy requires the three phases of preparing, responding and recovering. Only when a community has been able to adapt to the hazard can we begin to assess how resilient the community has been. Consequently, resilience requires that any community be able to prepare for, respond to and recover from a hydrologic hazard such as a high precipitation event.

As a case in point, prior to the 2006 storm events in Southern Johor, the Malaysian Meteorological Department (MMD) had already documented anomalous storms in several states in 2005 in addition to the data collected for the 2001 Vamei event. MMD noted that there had been "increasing number of days of extreme rainfall event (exceeding 90th percentile of total rainfall) for several stations over the Peninsular Malaysia" since the 1980s [50]. Although MMD had in place weather prediction systems as part of its monitoring system, the adaptation strategy was hardly effective as there was not yet a plan to identify vulnerabilities and risks. After the 2006 storm event, the Malaysian Ministry of Natural Resources and Environment (MNRE) started to develop "risk maps for vulnerable areas" [108]. Since then, a national level effort was undertaken to increase the adaptive capacity of the country through improving risk assessment, in order to formulate effective adaptation strategies.

4. CONCLUSION

In managing rainfall related hazards, droughts and extreme storms have been treated rather independently, perhaps due to the polarity in the amount of rainfall that each event brings. While the rainfall record has only shown more incidences of extreme storms with fewer examples of extremely dry events, the global rhetoric on climate change converges on an agreement on the certainty of changes to precipitation patterns across the world. There clearly will be areas that will be prone to extreme storms and others drought. Indeed, these two phenomena can occur in the same place at different times, with varying frequency. The examples outlined in this paper go to show that resilience is a concept that can be unraveled to include the components of preparing for, responding to and recovering from the extreme hydrologic events. In ecology, resilience refers to the capacity of the system to respond to a disturbance and resist the impact or recover from the damage of the disturbance. Indeed, with proper planning and preparation in building a system's capacity, there is opportunity to resist the impact of climate change. Failing which, the planned responses and recovery will ensure that the impact is minimized.

The authors are not suggesting that all countries need to have NEWater or desalinated water to solve drought problems but rather explicate the concepts in the steps that will make an adaptation strategy effective. For any community, the assessment of the risk, the building of adaptive capacity and the actual adaptation strategies must be included when designing an adaptation program for a particular hazard. It is also important to consider the feasibility of implementation, efficiency, efficacy, and legitimacy with stakeholders, equity and sustainability of the program [93]. There is not a one size fits all solution to sustainable water resource management.

The often quoted saying "that which does not kill us makes us stronger" by German philosopher Friedrich Nietzsche provides some insight on the concept of climate change resilience. As geographers, the authors subscribe to the view that the human-environment relationship is dynamic in nature. This relationship is not maintained at a static equilibrium in which things do not change. Indeed, the concept of adaptation for human-induced climate change requires an understanding of how climate change will impact humans. In building resilience, the fundamental premise is to either resist the impact, adapt to the impact, or to recover from the impact. The fundamental motivation for resilience is survival and it seems counter-intuitive that communities would subscribe to inaction as a way to respond to the changing weather patterns brought about by climate change. If humanity is to prevail despite adjustments to the dynamic equilibrium in our earth-atmosphere system, then we must remain resilient and take action for it.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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