National Environment Agency
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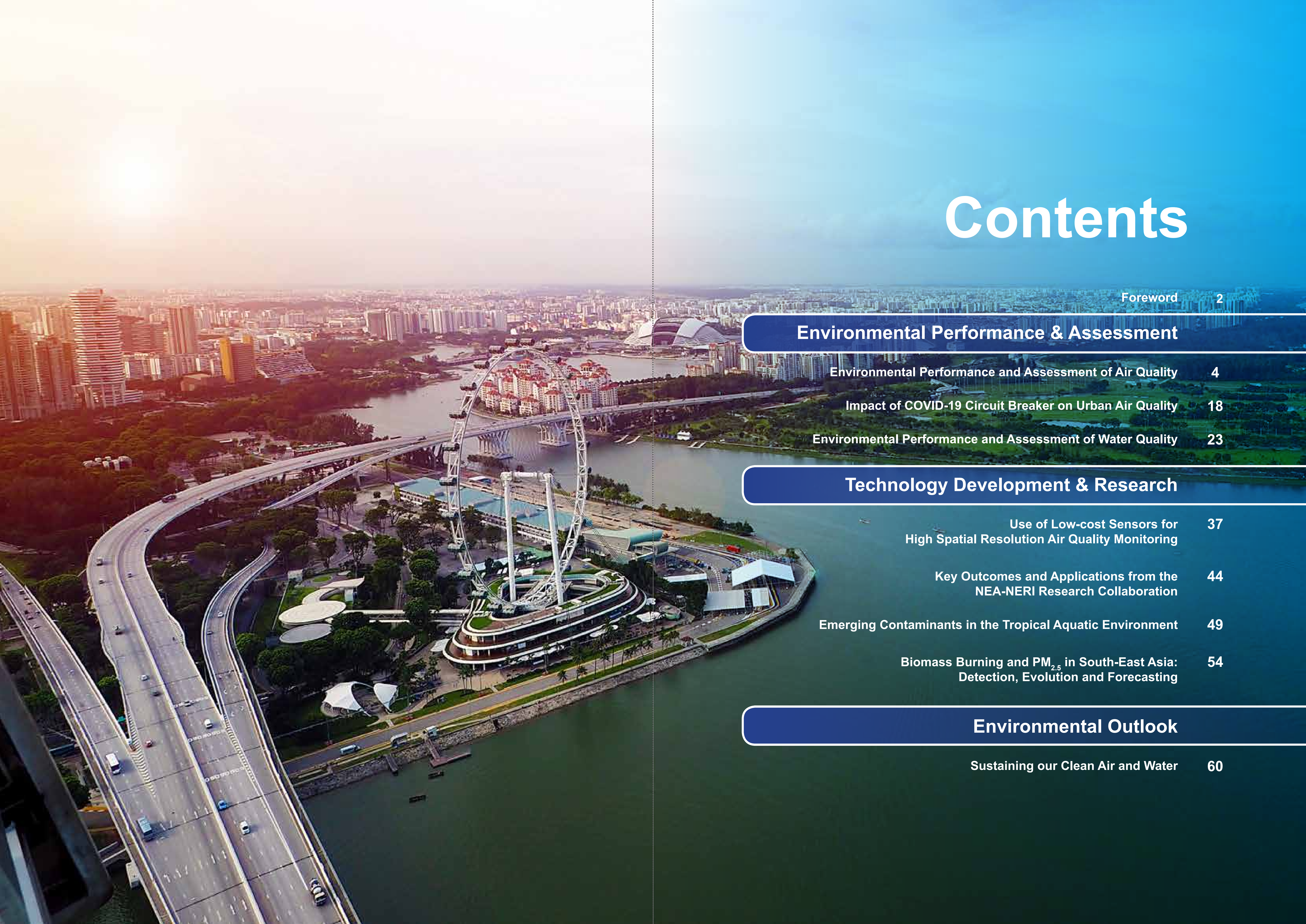
STATE OF THE ENVIRONMENT

AIR & WATER QUALITY

A REPORT BY NEA'S ENVIRONMENTAL MONITORING AND MODELLING DIVISION



Contents

Foreword

The Environmental Monitoring and Modelling Division (EMMD) monitors and assesses the quality of Singapore's ambient air and water bodies. As part of the National Environment Agency (NEA)'s Clean Environment Group, EMMD plays an integral role in safeguarding our clean environment. This includes upstream development planning and control, surveillance and enforcement, downstream environmental monitoring, modelling, and research, as well as review of policies for pollution management.

This inaugural State of the Environment Report provides an assessment of our ambient air and water quality performance and trends over the years. This report also highlights some efforts in furthering our capabilities through building a stronger base of technology and scientific research.

The publication also features articles contributed by various experts, providing their technical insights on Singapore's environmental performance. In particular, the COVID-19 pandemic provided a unique opportunity to study air and water quality when economic activities were reduced as a result of local and global movement restrictions. An article by Professor Rajasekhar Balasubramanian explores the impact of COVID-19 Circuit Breaker on urban air quality and provides insights on the contributing factors influencing the air quality performance in 2020. Other featured articles by Associate Professor Yu Liya, Associate Professor Karina Gin, and Dr Santo V. Salinas Cortijo share outcomes from their scientific research in understanding the characteristics of air pollutants, emerging water pollution concerns, and on the use of remote sensing technologies for environmental monitoring respectively.

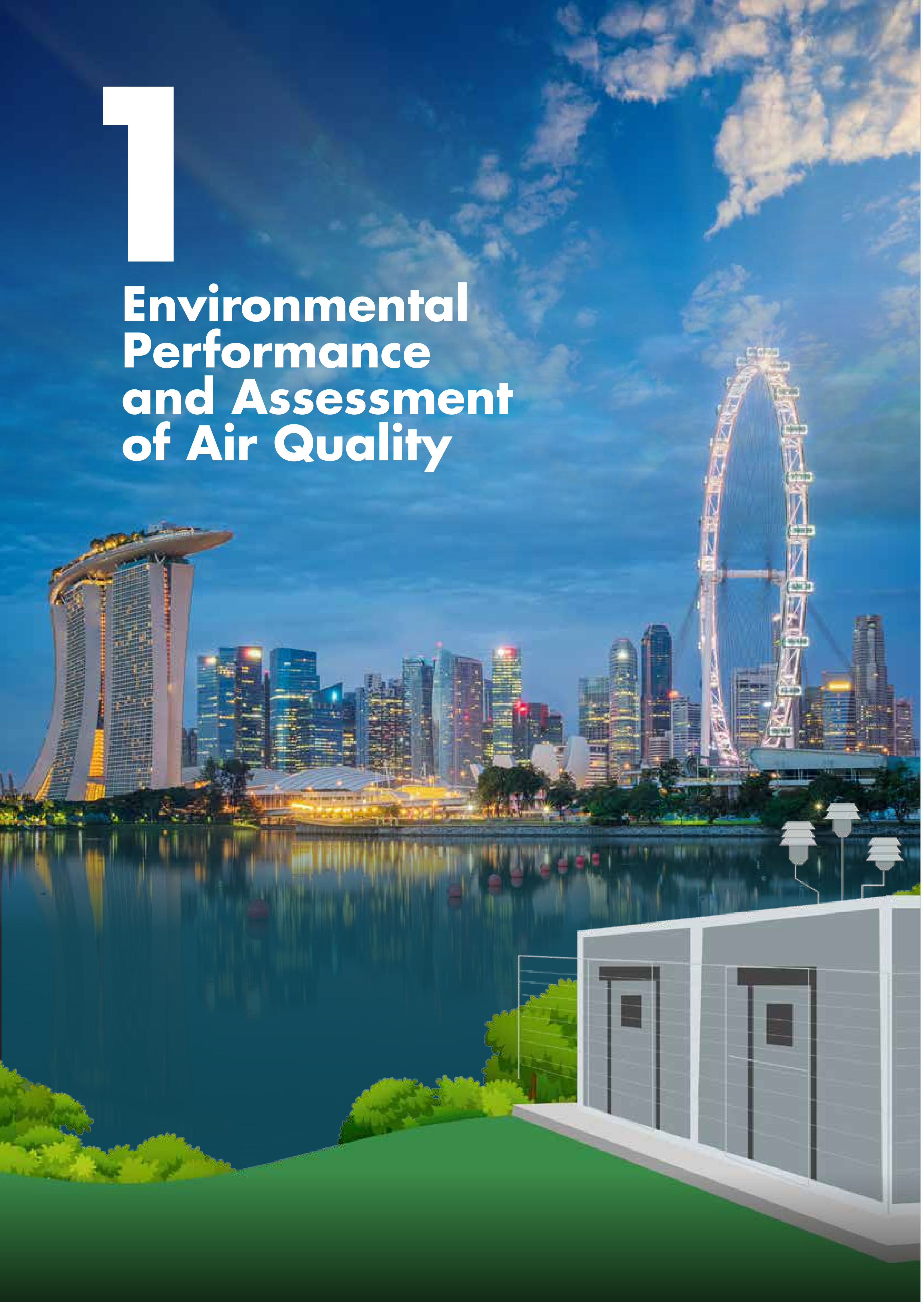
We hope that this publication would be the first of many more to come, where we share EMMD's current capabilities such as using atmospheric dispersion modelling to facilitate development planning and policy reviews. Potentially, readers can also find out more on our new capabilities such as leveraging dispersion modelling for chemical and odour incident investigations.

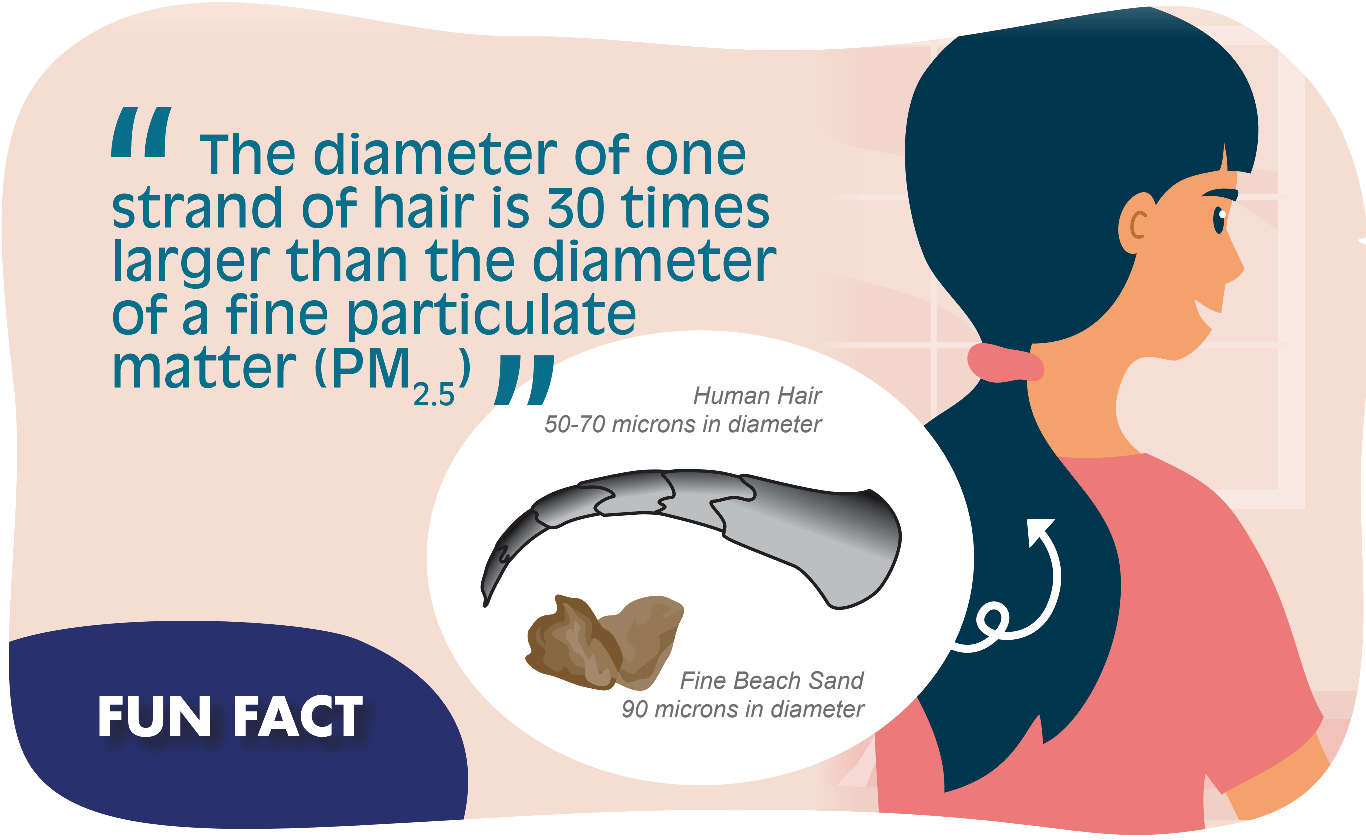
In conceptualising this publication, we had in mind anyone with an interest in Singapore's environmental quality. We hope that it succeeds in helping readers better understand how environmental monitoring is undertaken, and gain an appreciation of the unceasing efforts required to ensure a clean environment for all residents of Singapore to live, work, and play in. We further wish that the knowledge sharing here seeds further collaborations with our partners in the public, people, and private sectors to deepen our shared scientific knowledge and technical capabilities.

Jelita Teper

Director and Chief Scientific Officer
Environmental Monitoring & Modelling Division
National Environment Agency

1 Environmental Performance and Assessment of Air Quality





INTRODUCTION

The ambient air quality in Singapore is continuously monitored through a network of air monitoring analysers. These sensors measure the levels of six criteria air pollutants; namely sulphur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), carbon monoxide (CO) and particulate matter (both PM_{10} and $PM_{2.5}$), and a variety of volatile organic compounds (VOCs).

Apart from continuous air monitoring, NEA has a fortnightly manual air sampling programme to monitor the levels of lead in the ambient air, as well as an annual air sampling programme to monitor dioxin levels in ambient air.

NEA primarily benchmarks Singapore's air quality against the World Health Organisation


NEA's ambient air quality monitoring station provides continuous monitoring of our ambient air quality

Air Quality Guidelines (WHO AQG) and strives towards achieving the WHO AQG (2005) in the long term. The air quality performance for the following index and pollutants will be detailed in the sections that follow: Pollutant Standards Index

(PSI), particulate matter (PM_{10} and $PM_{2.5}$), SO_2, NO_2, CO, O_3, benzene, lead, and dioxins.

The air quality in Singapore is monitored and reported using the Pollutant Standards Index (PSI).

POLLUTANT STANDARDS INDEX (PSI)

The air quality in Singapore is monitored and reported using the PSI. The PSI is an index to provide easily understandable information about daily levels of air quality. The levels of the six criteria pollutants are continuously monitored and their concentrations over a 24-hour period are used to compute the 24-hour PSI.

The 24-hour PSI is accompanied with a health advisory that provides advice to the public on the general effects associated with atmospheric pollution, as shown below:

HEALTH ADVISORY FOR THE GENERAL PUBLIC

24-HOUR PSI DESCRIPTOR

	0-50 Good	51-100 Moderate	101-200 Unhealthy	201-300 Very Unhealthy	>300 Hazardous
HEALTHY PERSONS	Normal activities	Normal activities	**Reduce** prolonged or strenuous outdoor physical exertion	**Avoid** prolonged or strenuous outdoor physical exertion	**Minimise** outdoor activity
ELDERLY, PREGNANT WOMEN, CHILDREN	Normal activities	Normal activities	**Minimise** prolonged or strenuous outdoor physical exertion	**Minimise** outdoor activity	**Avoid** outdoor activity
PERSONS WITH CHRONIC LUNG DISEASE, HEART DISEASE	Normal activities	Normal activities	**Avoid** prolonged or strenuous outdoor physical exertion	**Avoid** outdoor activity	**Avoid** outdoor activity

Figure 1. *Health advisory for the general public*

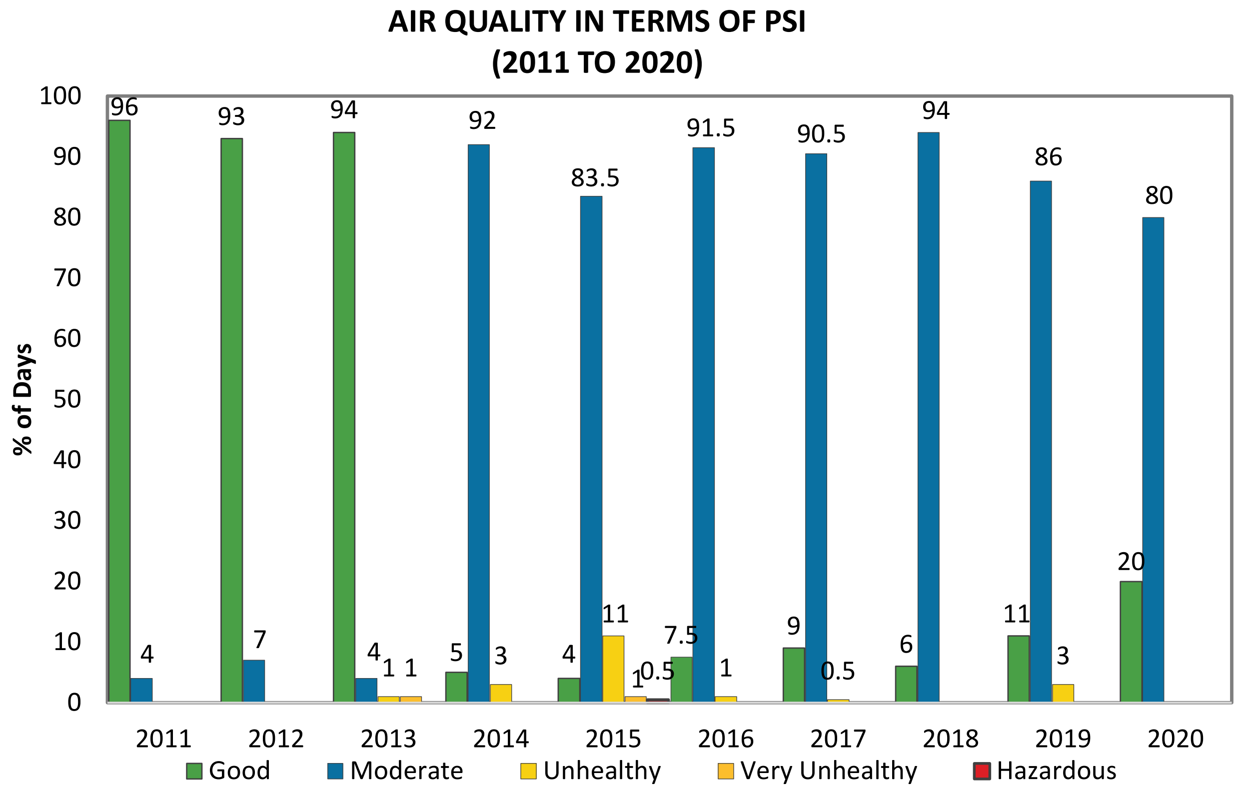


Figure 2. Air Quality in terms of PSI

- *Air quality was affected by transboundary haze from the region in 2013, 2014, 2015, 2016 and 2019.*
- *In 2014, Singapore included $PM_{2.5}$ in the computation of PSI, in addition to the then existing five pollutants. Its inclusion resulted in a lower percentage of days being in the good range.*

Air quality was in the "Good" and "Moderate" ranges on all the days of 2020.

2020 PERFORMANCE

Air quality was in the "Good" and "Moderate" ranges on all the days of 2020, as shown in Figure 2. One of the possible reasons for the improvement in air quality from the previous years is the reduction of economic and transport activities due to the COVID-19 situation over most of 2020. Relatively wet weather during the traditional dry season in the second half of the year also helped to keep pollutant levels down. The subsequent sections of this chapter will detail the performance of the six criteria air pollutants used in the computation of the 24-hour PSI and other key air pollutants monitored, and analyse possible reasons for their performance.

PARTICULATE MATTER (PM_{10} AND $PM_{2.5}$)

Particulate matter refers to the mixture of solid and liquid particles in the air. These particles are categorised according to size. PM_{10} refers to particulate matter of size 10µm or below in diameter. These can be inhaled, with some depositing throughout the airways and in the lungs. Fine particulate matter, $PM_{2.5}$, are particles that are 2.5µm or less in diameter. These particles can penetrate the deeper regions of the respiratory tract when inhaled. At elevated levels, the particles cause breathing and respiratory problems, and can aggravate existing respiratory and cardiovascular diseases.

1-HOUR $PM_{2.5}$ PERSONAL GUIDE

The 1-hour $PM_{2.5}$ concentration is the average concentration of $PM_{2.5}$, in micrograms per cubic metre (µg/m³), measured in the air over the past hour. Since 2014, NEA has been publishing the 1-hour $PM_{2.5}$ concentrations on an hourly basis across the five regions in Singapore. The 1-hour $PM_{2.5}$ concentration is a useful indication of the current air quality. In 2016, NEA introduced bandings and descriptors for the 1-hour $PM_{2.5}$ concentrations to help the public interpret the readings.

In 2020, NEA and the Ministry of Health (MOH) jointly developed a personal guide to the 1-hour average concentration of fine particulate matter ($PM_{2.5}$) to help individuals decide on their immediate outdoor activities, especially during the haze season, as shown in Figure 3 below.

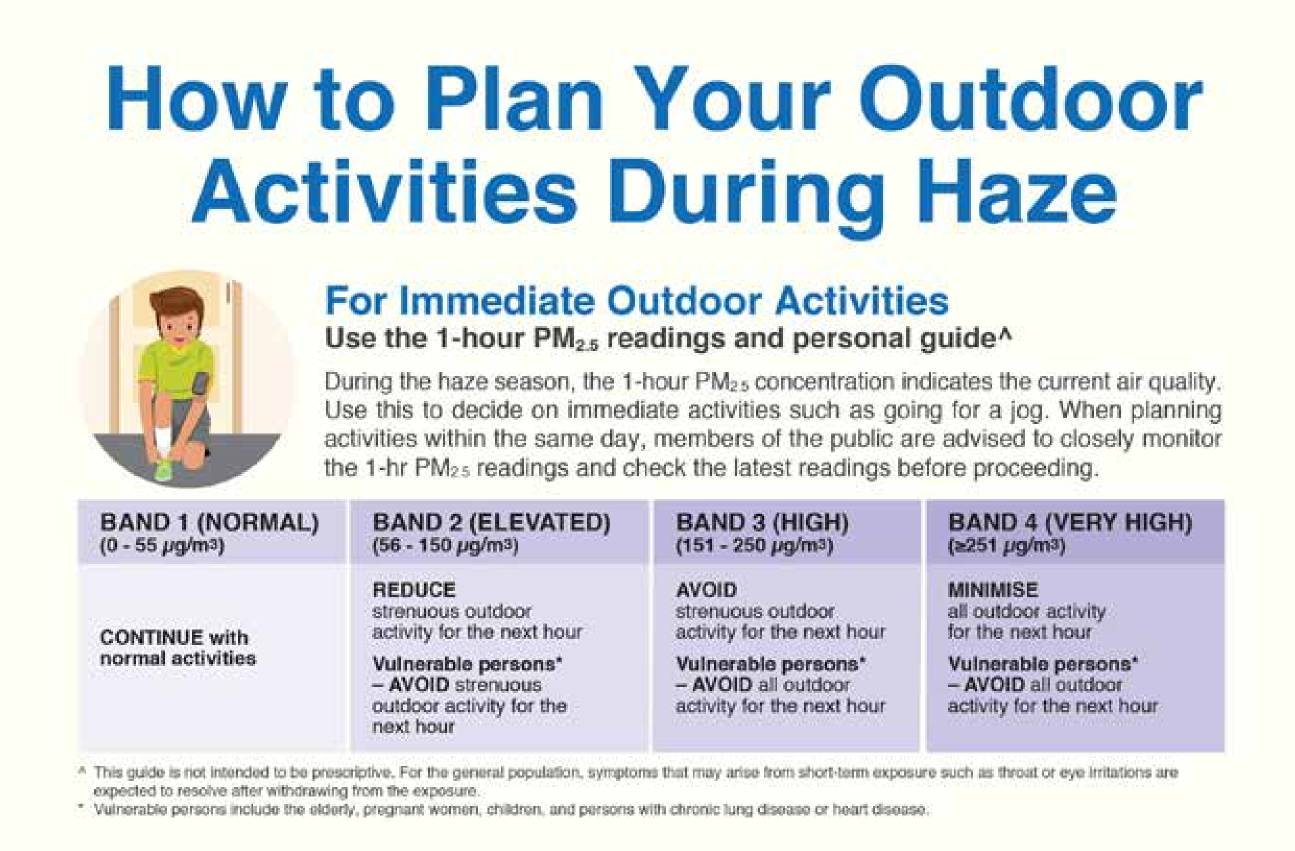


Figure 3. *1-hour $PM_{2.5}$ personal guide*

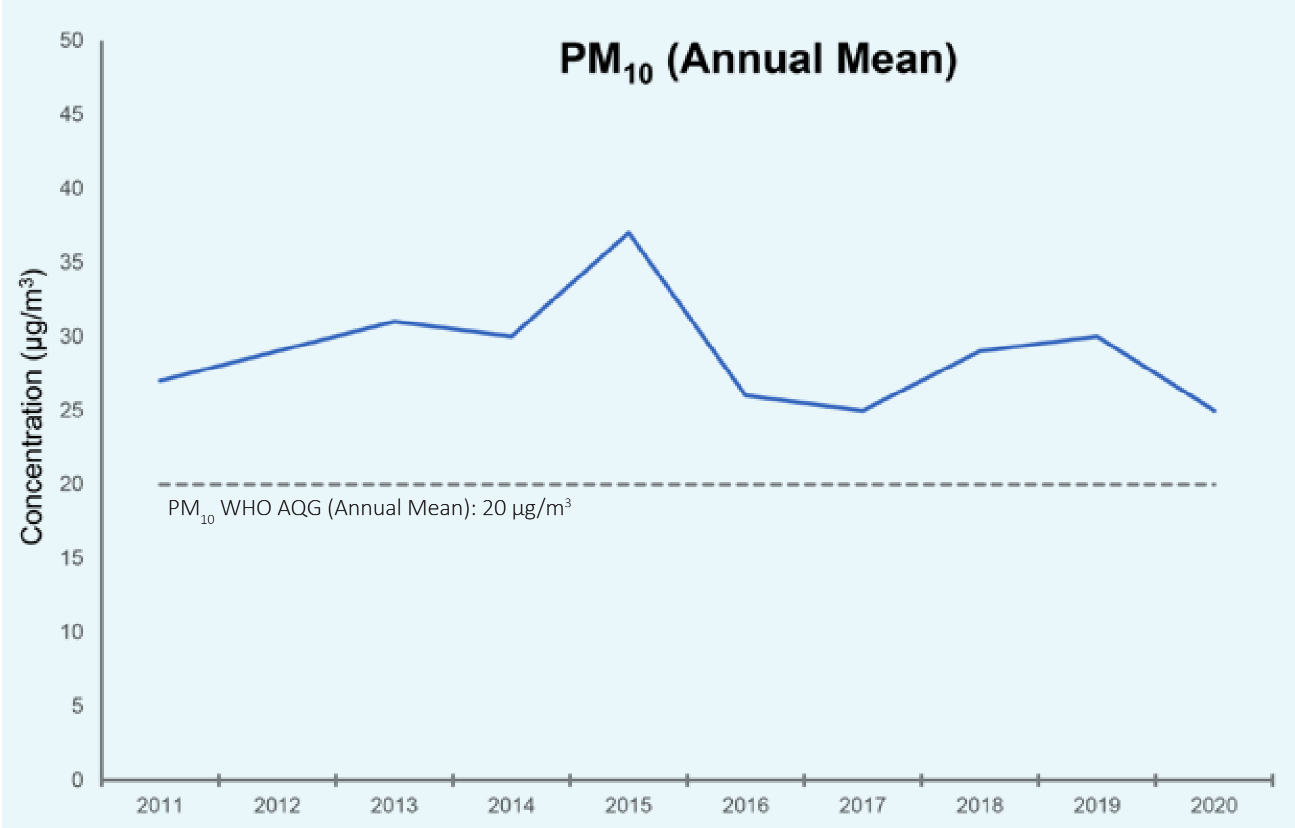


Figure 4. *PM_{10} Annual Mean*
- *Air quality was affected by transboundary smoke haze in 2013, 2014, 2015, 2016 and 2019*
- *PM_{10} annual mean is based on the average values of all 1-hour PM_{10} concentrations for all regions in a year*

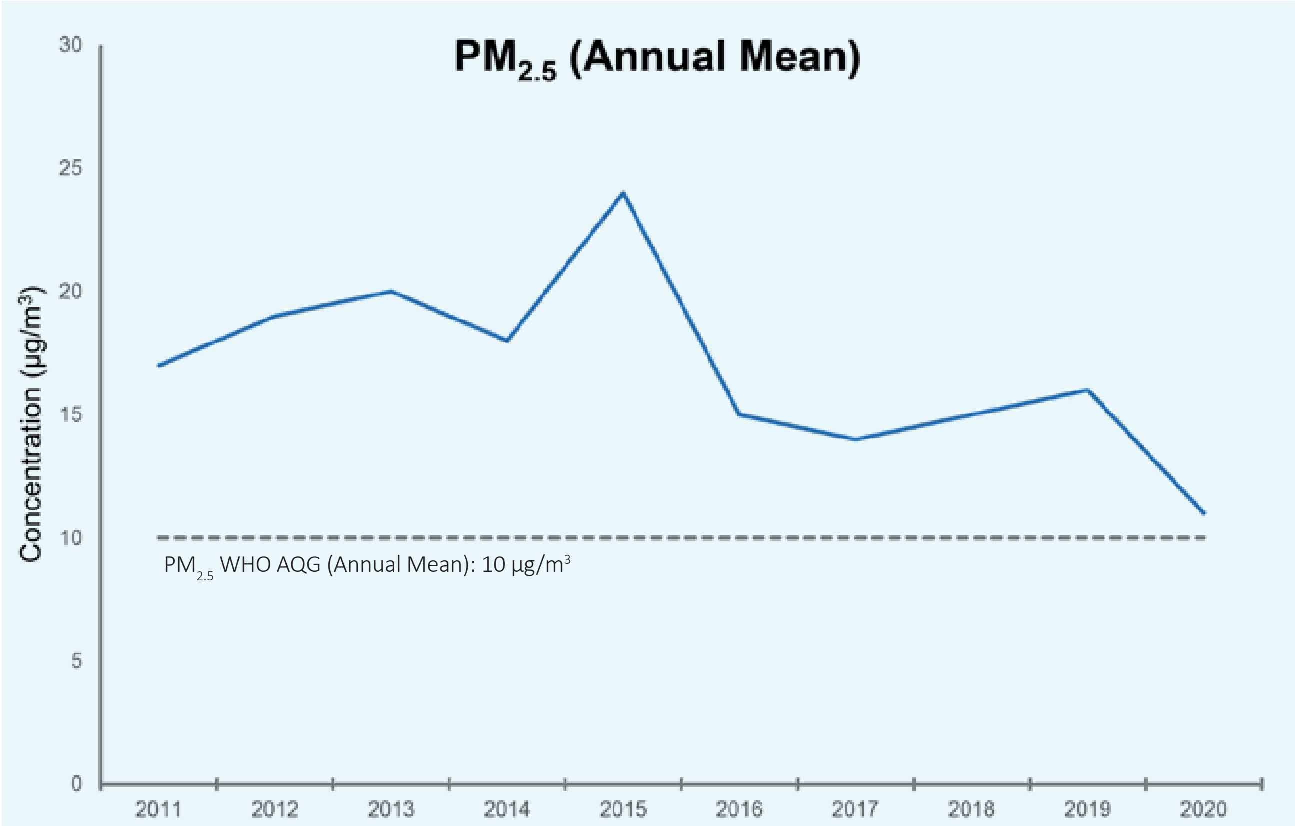


Figure 5. *$PM_{2.5}$ Annual Mean*
- *Air quality was affected by transboundary smoke haze in 2013, 2014, 2015, 2016 and 2019*
- *$PM_{2.5}$ annual mean is based on the average values of all 1-hour $PM_{2.5}$ concentrations for all regions in a year*

2020 PERFORMANCE

In 2020, the annual mean PM_{10} and $PM_{2.5}$ levels exceeded the WHO AQG (2005) values. However, they were the lowest recorded over the last 10 years. The significant improvement in 2020 was likely due to the reduced levels of of industrial activities and vehicular traffic.

Apart from the elevated levels in years affected by severe transboundary haze, the trend shows that the levels of PM_{10} and $PM_{2.5}$ have been decreasing over the past decade. Industries and motor vehicles are the major sources of PM_{10} and $PM_{2.5}$ in Singapore. Over the years, a multi-pronged approach involving the tightening of vehicular emission standards, fuel quality standards, and stringent enforcement action against smoke emissions from motor vehicles and industries, have reduced domestic emissions of PM.

For example, NEA adopted the Euro VI emission standards from 1 September 2017 for petrol vehicles, and introduced the Vehicular Emission Scheme (VES) in 2018 to encourage buyers to choose car models with lower emissions across five pollutants, including PM.

SULPHUR DIOXIDE (SO_2)

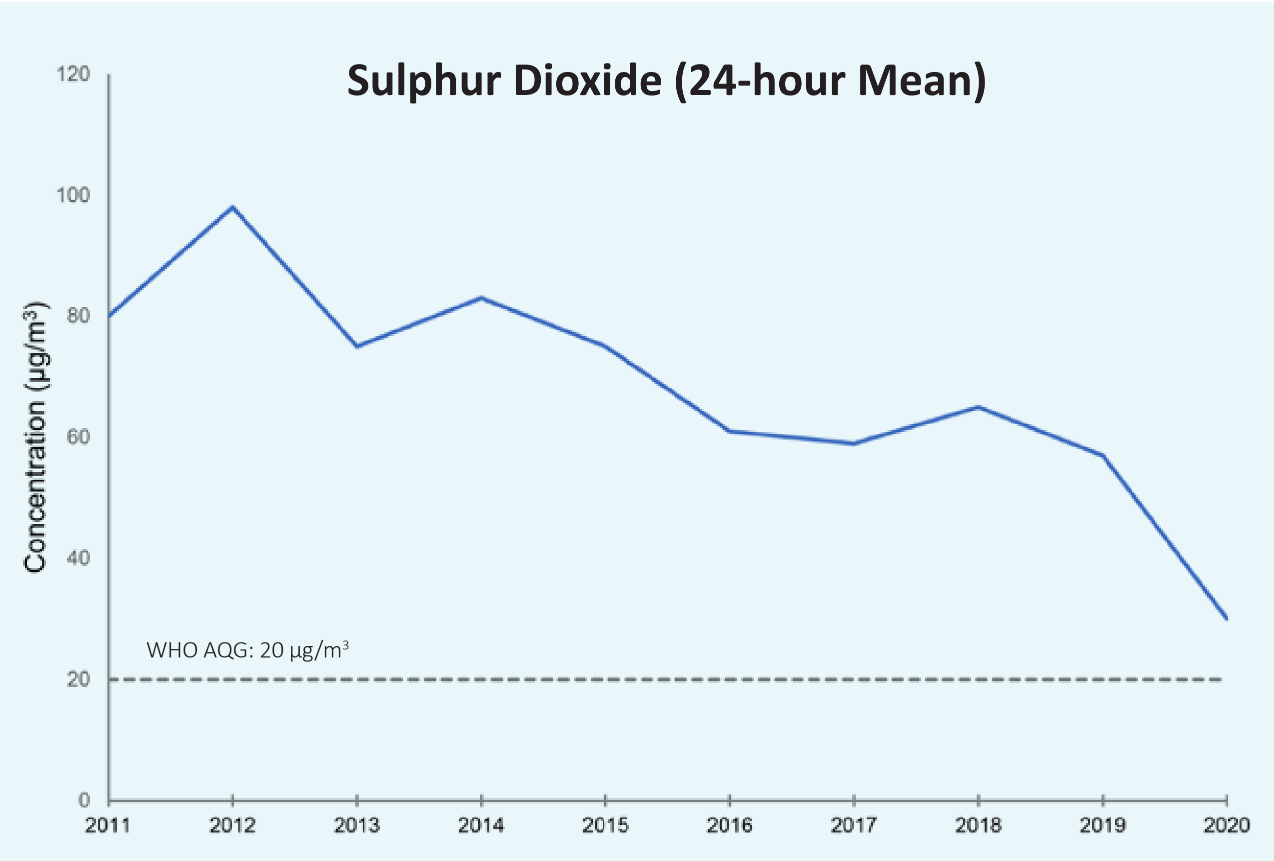


Figure 6. *Sulphur Dioxide (24-hour Mean)*
- *24-hour mean is the average of hourly readings taken over 24 hours. The 24-hour mean levels referred to in the chart is the highest 24-hour mean recorded for the year.*

2020 PERFORMANCE

Singapore's maximum 24-hour SO_2 mean in 2020 was 30 µg/m³, the lowest over the past 10 years. However, Singapore is still unable to meet the WHO AQG (2005) value of 20 µg/m³.

Industrial and shipping activities are the main sources of Singapore's SO_2 emissions. The reduction of industrial activities was the likely key reason for the improved performance.

In addition, from 1 January 2020, the International Maritime Organisation (IMO) introduced a lower sulphur limit of 0.50%m/m for fuel oil used by ships, reducing SO_2 emissions from the shipping industry.

SO_2 levels in ambient air have been steadily improving over the last 10 years.

NEA has been working with industries to lower emissions through the tightening of industrial SO_2 standards to 1,700 mg/Nm³ in 2015 for new industrial plants and by 2023 for existing industrial plants. Power stations have also moved towards using cleaner fuels such as natural gas, which emits less SO_2 compared to other fuels such as fuel oil or diesel.

Fuel sulphur limits in diesel vehicles have also been reduced from 0.005% to 0.001% from 2013, while petrol sulphur limits in motor vehicles were reduced to 0.005% in 2013, and further reduced to 0.001% from 2017[1].

NITROGEN DIOXIDE (NO_2)

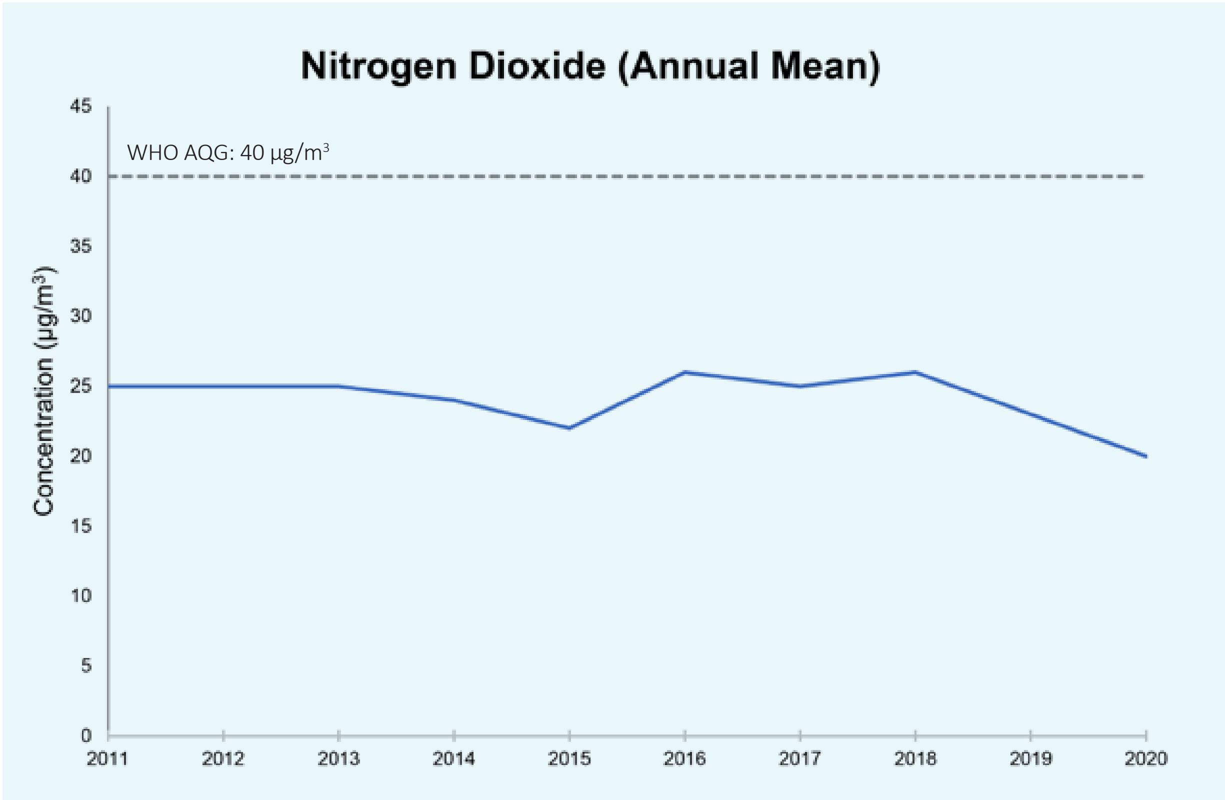


Figure 7. *Nitrogen Dioxide (Annual Mean)*

[1] https://www.nea.gov.sg/our-services/pollution-control/air-pollution/air-quality

2020 PERFORMANCE

The annual NO_2 mean of 20 µg/m³ in 2020 was the lowest it has been in the last 10 years.

NO_2 is mainly emitted from the burning of fuel during combustion processes in industries, and from engines of vehicles. Hence, the reduction of industrial and transportation activities in 2020 would have contributed to the improvement in levels.

Singapore has been meeting the WHO AQG (2005) value of 40 µg/m³ over the past decade.

NEA's range of pollution control measures continues to ensure that NO_2 levels are kept low. Apart from the vehicular emission measures mentioned above, the industrial NO_2 emission standard was tightened from 700 mg/Nm³ to 400 mg/Nm³ in 2015 for new industrial plants, and by 2023 for existing industrial plants.

CARBON MONOXIDE

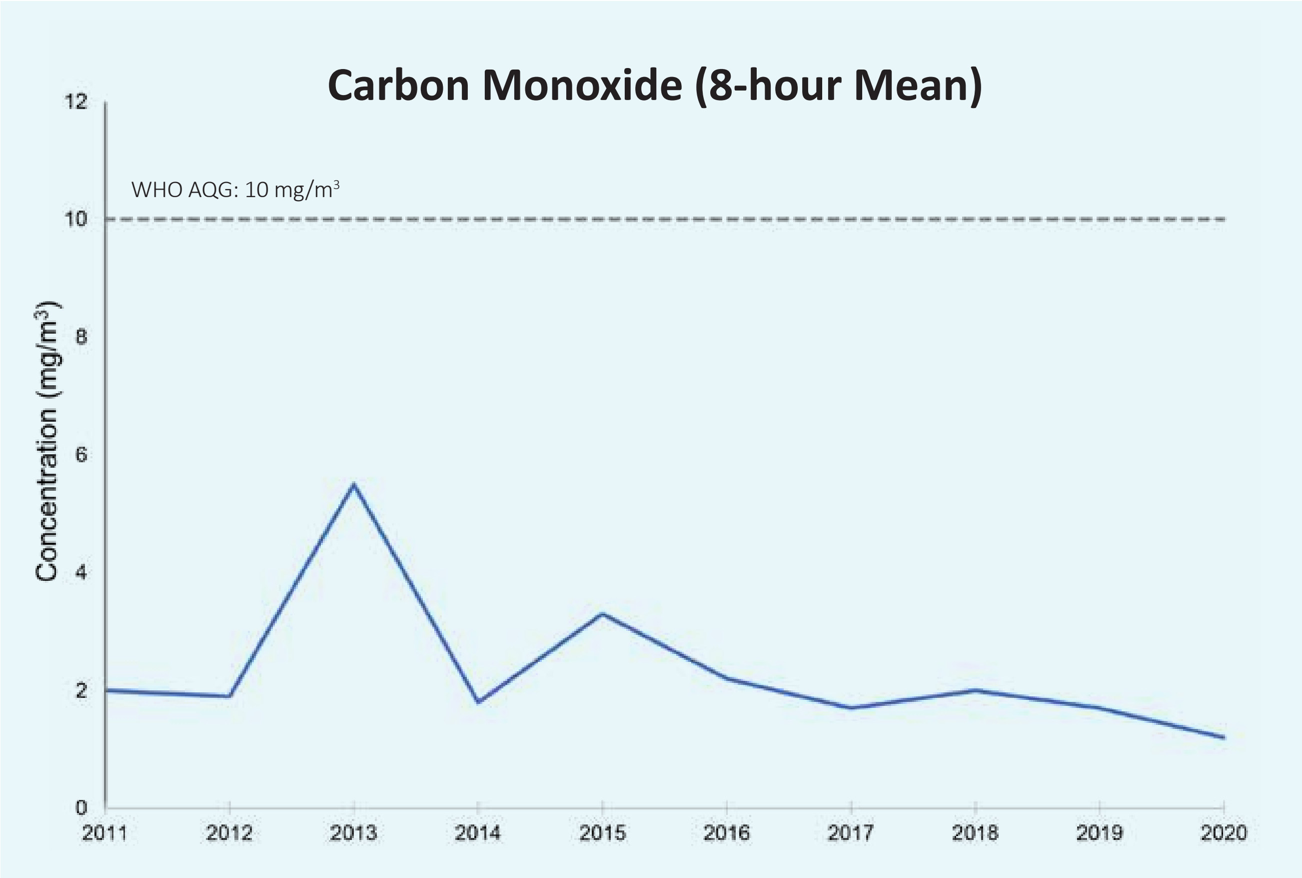


Figure 8. *Carbon Monoxide (8-hour Mean)*
- *8-hour mean is the average of hourly readings taken over 8 hours. The 8-hour mean levels referred to in the chart is the highest 8-hour mean recorded for the year.*

2020 PERFORMANCE

Singapore's maximum 8-hour mean for CO in 2020 was 1.2 mg/m³, well within the WHO AQG (2005) value of 10 mg/m³. It was also the lowest recorded concentration over the last 10 years.

CO is formed from incomplete combustion of carbon-containing fuels and, like NO_2, is mainly emitted from combustion processes of industries, and engines of vehicles. As such, the improvement was likely due to 2020's reduced industrial and transportation activities.

Singapore's CO level has been stable and well within the CO target over the last decade, although elevated levels were recorded in 2013 and 2015 due to forest and peat land fires in the region. Although Singapore has been consistently performing well in ambient CO levels, it remains important to keep CO levels low since it is a precursor to the formation of ozone. The industrial CO standard was tightened from 625 mg/Nm³ to 250 mg/Nm³ in 2015 for new industrial plants, and will similarly be tightened by 2023 for existing industrial plants. Under the Motorcycle Deregistration Incentive Scheme, NEA also provides incentives to owners of older motorcycles, which account for 50% of CO emissions from vehicles despite accounting only for 15% of the local vehicle population, to deregister their motorcycles early.

GROUND-LEVEL OZONE

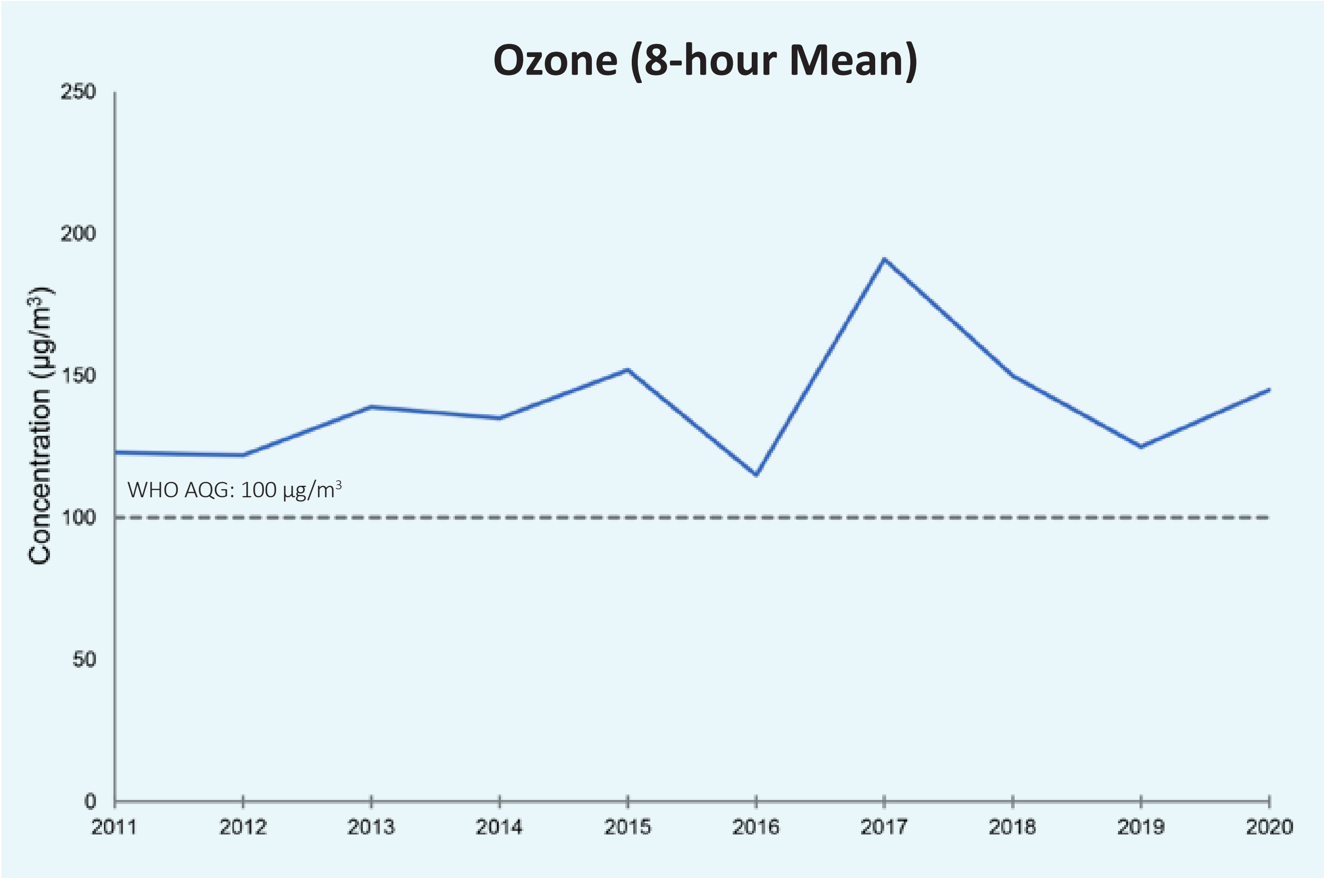


Figure 9. *Ozone (8-hour Mean)*
- *8-hour mean is the average of hourly readings taken over 8 hours. The 8-hour mean levels referred to in the chart is the highest 8-hour mean recorded for the year.*

2020 PERFORMANCE

In 2020, while the other pollutants decreased, the ozone level increased compared to 2019.

Unlike the other pollutants, ozone is a secondary pollutant. It is not directly emitted from a source but is formed in the troposphere as a result of complex atmospheric chemical reactions involving NO_x and VOCs in the presence of sunlight. This makes it challenging to attribute ozone level changes to individual sources or causes. The increase in ozone levels in 2020 was a common occurrence around the world. This was related to reduced NO_x levels globally in 2020, which led to reduced reactions between NO_x and ozone, resulting in less ozone being removed from the atmosphere[2]. These complex relationships between ozone and other pollutants in the atmosphere has made the management of ozone levels in ambient air a challenge for many countries.

ASSESSMENT OF LONG-TERM PERFORMANCE

Singapore has not been able to meet the WHO AQG (2005) for maximum 8-hour ozone mean of 100 $\mu g/m^3$. There is no clear trend observed in the annual levels over the last 10 years.

Due to the nature of ozone and its complex formation processes, management of ambient ozone levels is challenging. Nonetheless, NEA has put in place various measures to reduce its precursor pollutants (namely NO_x, CO and VOCs), and will continue to work with researchers to better understand ozone formation in Singapore.

BENZENE

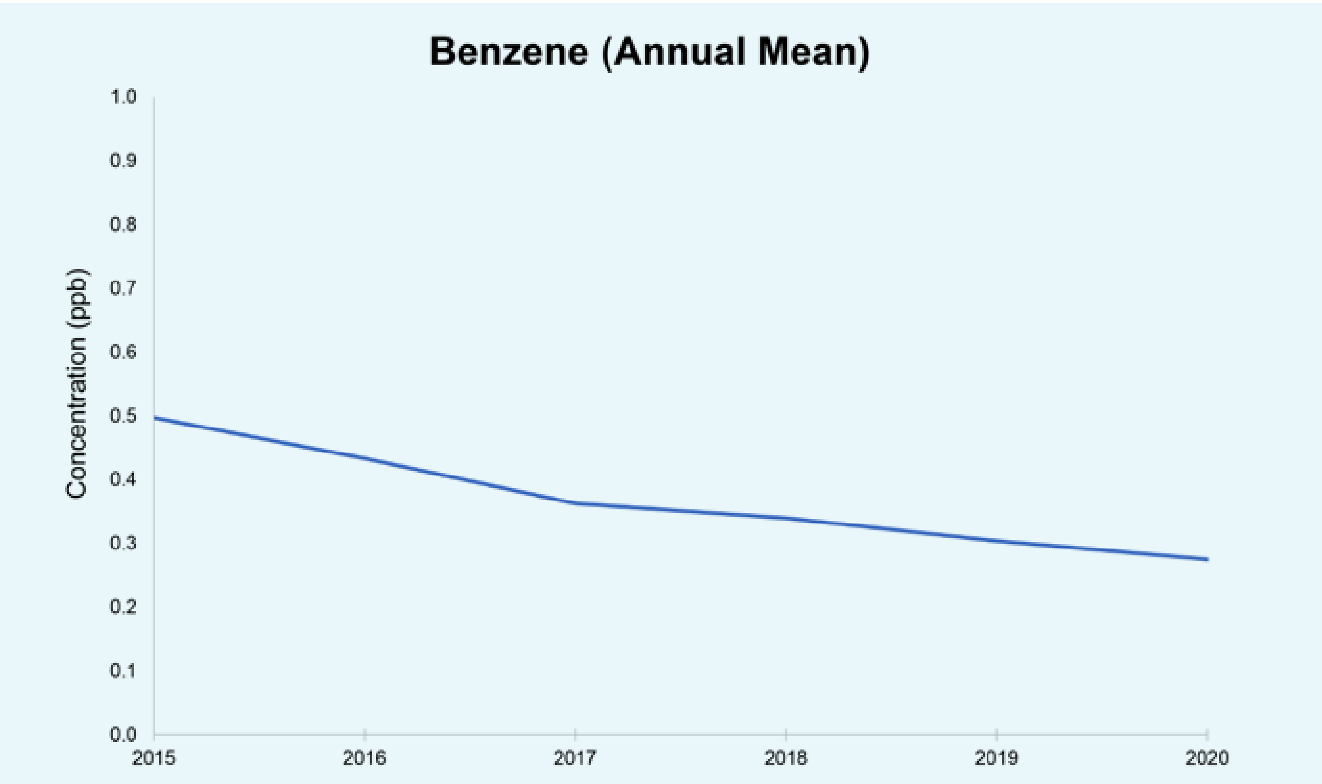


Figure 10. *Benzene (Annual Mean)*
- *The benzene annual mean is based on the average of hourly readings recorded for the year.*
- *National monitoring for benzene began in 2015.*

[2] https://www.pnas.org/content/117/32/18984

Benzene is a VOC that occurs naturally in crude petroleum and is emitted through the processing and burning of petroleum products, with a wide range of sources like petrochemical industries, motor vehicle exhausts, and tobacco smoke. Benzene is a widely monitored VOC due to its carcinogenicity.

2020 PERFORMANCE

The average ambient benzene concentration in 2020 was 0.28 ppb, the lowest recorded since monitoring began in 2015. This is partly due to the reduction in petrochemical industrial and transportation activities last year. The WHO does not set ambient air exposure limits for benzene. However, several countries have produced their own benzene guideline limits, which Singapore benchmarks against. Singapore's benzene levels for the last five years range between approximately 0.3 – 0.5 ppb, which are below the guideline limits of most countries compared against, including the EU.

Over the longer term, annual mean benzene concentrations have been decreasing since 2015. NEA imposes an emission limit for benzene of 5 mg/Nm^3 on industries. In 2017, NEA implemented a 1% by volume benzene limit in petrol.

LEAD

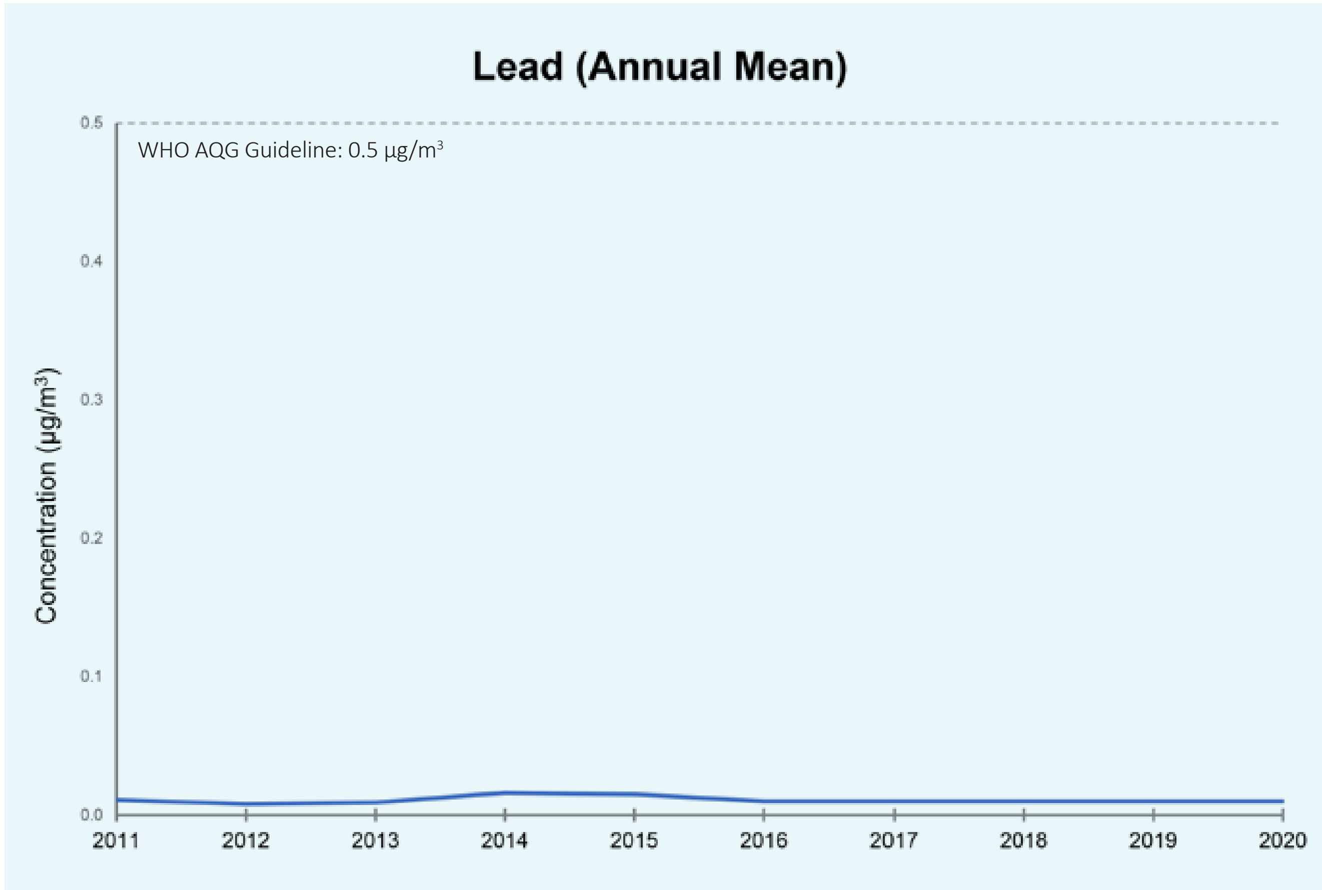


Figure 11. *Lead (Annual Mean)*

2020 PERFORMANCE

The ambient level of lead was 0.01 µg/m³ in 2020, consistent with the levels over the past decade and far below the WHO AQG value.

The combustion of leaded petrol used to be the main source of emission of lead particulates into the air. Since the phasing out of leaded petrol in 1998, lead levels in ambient air have stabilised to below 0.1 µg/m³, well within guideline value of 0.5 µg/m³.

DIOXINS

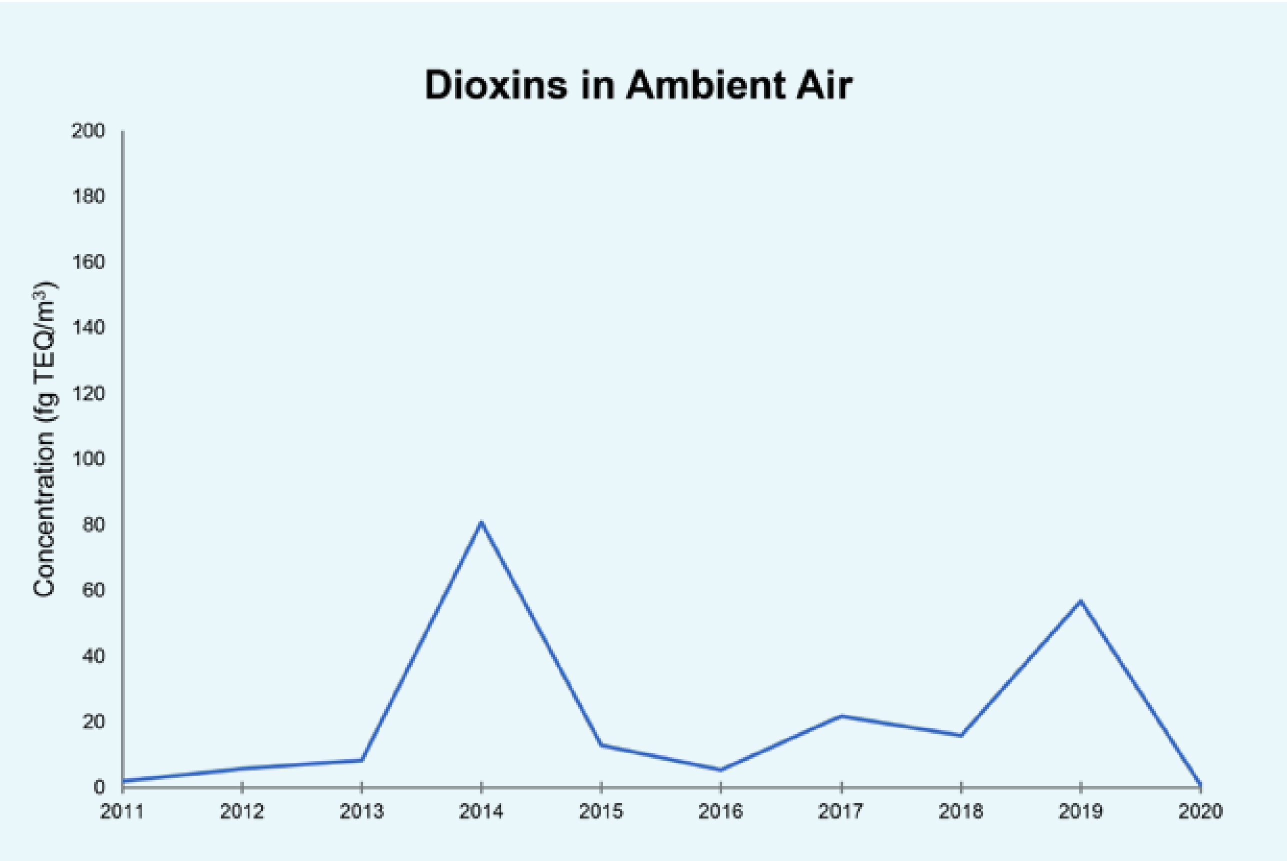


Figure 12. *Dioxins (Annual Mean)*

The term "dioxins" is commonly used to refer to the family of structurally and chemically similar polychlorinated dibenzo para dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs). They are known to be persistent organic pollutants (POPs) with high toxic potential. Human exposure to dioxins is mostly through food, although these chemicals can also be released into the air through incineration of waste or other fuel combustion processes.

2020 PERFORMANCE

The concentration of dioxins in 2020 was 0.8 fg-TEQ[5]/m³, the lowest recorded level in the last decade. This could have been due to the slowdown of economic activities during COVID-19 and reduction in waste generation compared to previous years.

The recorded levels of dioxins are generally low, less than 100 fg-TEQ/m³, and well within Japan's standard of 600 fg-TEQ/m³. There is currently no WHO AQG established for dioxins. The low levels could be attributed to stringent enforcement and emission limits placed on industries, including incineration plants, which can emit dioxins as a by-product[3]. These are done in compliance with the international Stockholm Convention on Persistent Organic Pollutants, of which Singapore is signatory since 2001[4].

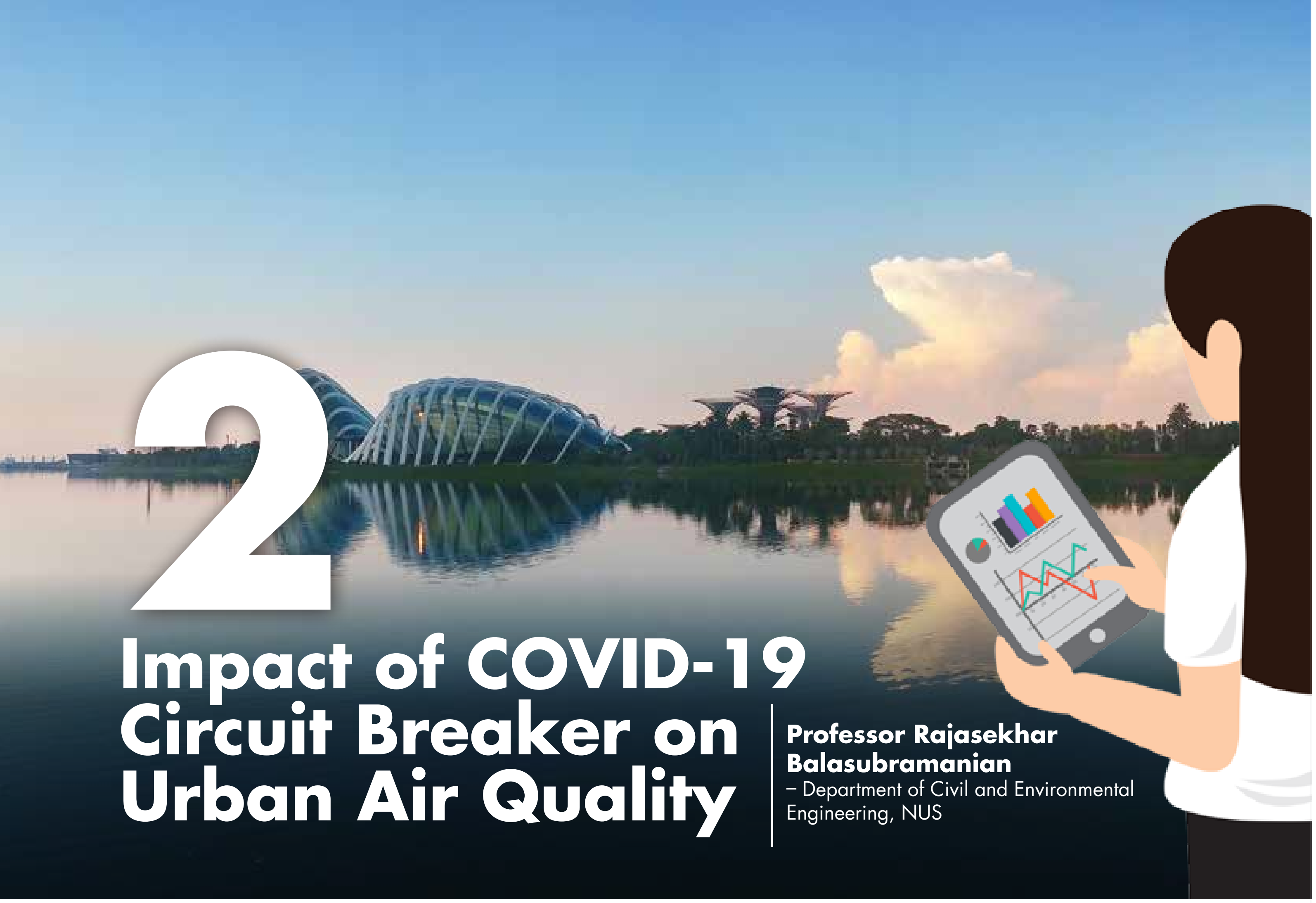
CONCLUSION

Air quality in 2020 improved compared to previous years, due to the slowdown of economic and transport activities over most of the year. While Singapore was able to meet the WHO AQG (2005) limits for NO_2 and CO, the limits for PM, SO_2 and ozone were exceeded. NEA will continue to monitor the ambient air quality and review measures to further improve the air quality to meet the long-term ambient air quality targets.

[3] https://va.ecitizen.gov.sg/CFP/CustomerPages/NEA_google/displayresult.aspx?MesId=1070291&Source=Google&url=va.ecitizen.gov.sg

[4] https://www.nea.gov.sg/corporate-functions/resources/legislation-international-law/multilateral-environmental-agreements/chemical-safety stockholm-convention

[5] TEQ (toxic equivalency) values are used to measure the toxicity of different dioxins and dioxin-like compounds. A toxic equivalent factor (TEF) is assigned to each dioxin and dioxin-like compound and the TEQ is calculated by multiplying the weight (in grams) of each compound by its corresponding TEF and adding the results.



2 Impact of COVID-19 Circuit Breaker on Urban Air Quality

Professor Rajasekhar Balasubramanian
– Department of Civil and Environmental Engineering, NUS

The COVID-19 pandemic forces a re-examination on how human activities has influenced air quality in our environments.

The COVID-19 pandemic, caused by SARS-CoV-2 (Severe Acute Respiratory Syndrome Coronavirus 2), and subsequent control measures (for example, travel restrictions, telecommuting and social distancing) implemented in countries worldwide in 2020 provided an unprecedented opportunity to examine how human activities influence air quality in urban environments. Many cities reported improvements in air quality during this period due to reduction in the levels of primary air pollutants directly emitted from human-induced air pollution sources. Surprisingly, the concentration of secondary air pollutants such as ground-level ozone (O_3) increased under blue skies in some cities; secondary air pollutants are not directly emitted, but formed in air due to complex chemical reactions.

The air quality in Singapore was studied to assess the impact of a two-month Circuit Breaker (CB) implemented from 7th April to 1st June 2020 to curb the local transmission of COVID-19. Reductions in the atmospheric levels of outdoor air pollutants such as fine particulate matter ($PM_{2.5}$) (-28.8%), nitrogen dioxide (NO_2) (-38.1%), carbon monoxide (CO) (-5.6%) and sulfur dioxide (SO_2) (-58.1%) were observed during the CB period compared to the same time period in the previous three years (from 2017 to 2019) (see Figure 1). Consequently, the Pollutant Standards Index (PSI), an indicator of ambient air quality, decreased by 21.4%. The reduction in the levels of $PM_{2.5}$ and NO_2 was mainly influenced by the reduced human movement on road, as revealed by the mobility data obtained from Google, Apple, and Singapore Housing and Development Board (Li and Tartarini, 2020) and traffic congestion information from TomTom traffic service (TomTom Int, 2021) (see Figure 2). The changes in the concentrations of CO and SO_2 could be attributed to the influence of other pollution sources such as industries, petroleum refineries and shipping-related activities in Singapore.

In contrast to the primary air pollutants, the concentration of secondary pollutant - ground-level O_3, an air pollutant linked to asthma and respiratory ailments, increased in Singapore by +12.0%. A similar observation was made in several other

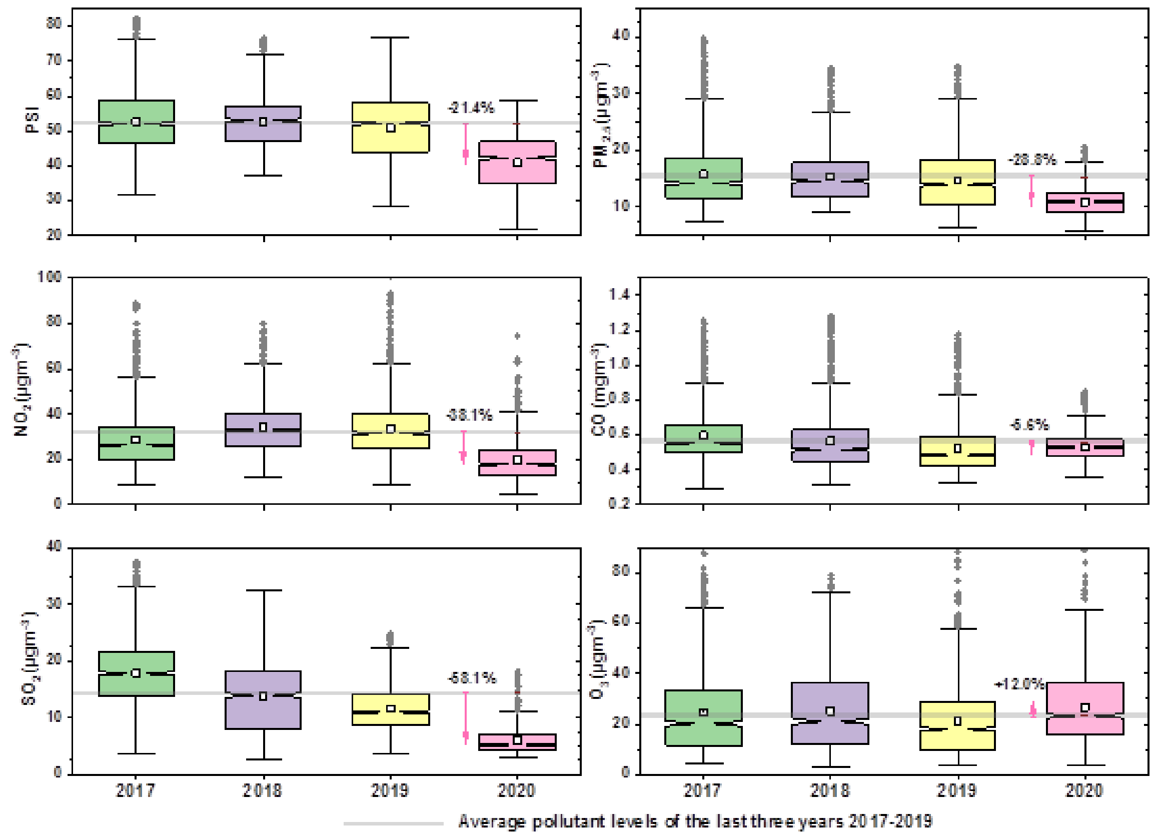


Figure 1. *Average concentrations of air quality parameters (including 24-hour PSI, 24-hour $PM_{2.5}$, 1-hour NO_2, 8-hour CO, 24-hour SO_2, 8-hour O_3) for the period of 7th April - 1st June from 2017 to 2021. Data were obtained from National Environment Agency (2021).*

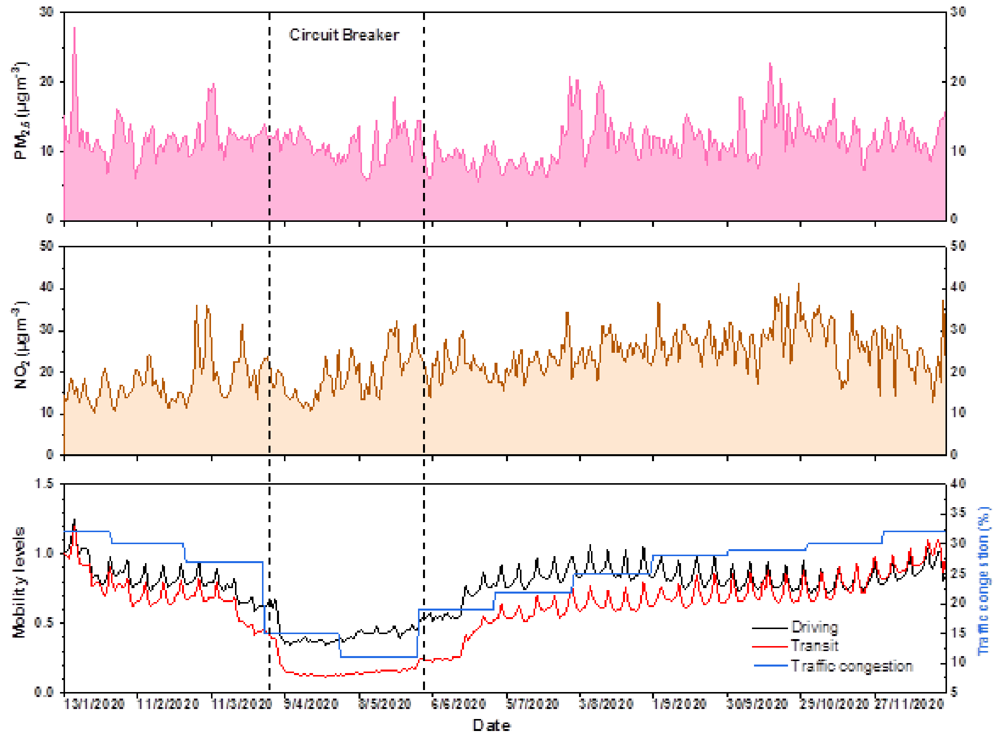


Figure 2. *Daily trend of air quality parameters (including $PM_{2.5}$, NO_2), mobility levels (driving and public transit) and traffic congestion level in 2020. Data were obtained from National Environment Agency (2021), Apple Inc. (2021) and TomTom Int. (2021)*

cities which implemented a lockdown (Chen et al., 2020; Dantas et al., 2020; Kerimray et al., 2020). It should be noted that weather parameters including ambient temperature, relative humidity, rainfall, and wind direction did not change significantly in 2020 compared to those recorded during the same period in previous years (Li and Tartarini, 2020; Meteorological Service Singapore, 2021).

Atmospheric chemical transformations played an important role in enhancing the formation of O_3 in urban air. O_3 is created in the atmosphere via complex reactions between nitrogen oxides (NO_X) and volatile organic compounds (VOCs) in the presence of sunlight. Several factors might have contributed to the counter-intuitive trend of increased O_3 levels in Singapore. Firstly, the O_3 production is a non-linear function of NO_X and VOCs. Consequently, reductions in the emissions of these precursors (NO_X and VOCs) can decrease or increase or leave the rate of O_3 production unchanged (Pusede and Cohen, 2012). Urban areas are generally characterised by a low VOC/NO_X ratio due to high NO_X concentrations driven by emissions from vehicles (Sillman, 1999). However, due to the decrease in NO_X emissions from local road transport, it is plausible that O_3 generation was enhanced in Singapore because of favourable atmospheric photochemcial transformations with a high VOC/NO_X ratio. A recent chemical transport modelling study simulated atmospheric dynamical processes and photochemical transformations in urban envionments and demonstrated that reduced precursors could cause enhanced formation of secondary air pollutants such as O_3 due to the elevated oxidising capacity of the atmosphere (Huang et al., 2021).

Secondly, the decrease in observed $PM_{2.5}$ levels might have led to an increase in incoming solar radiation due to lack of light scattering and absorption (light extinction) and thus increased the photochemical production of ozone as has been reported in other urban environments (Jia et al., 2017; Wang et al., 2020). Lastly, the lower $PM_{2.5}$ levels in Singapore presumably suppressed the removal of active atmospheric free radicals such as hydroxyl radicals (OH.) and hydroperoxyl radicals (HO_2.), contributing to enhanced formation of O_3 via the free radical pathways (Sicard et al., 2020). It is therefore necessary to integrate O_3 and $PM_{2.5}$ controls to ensure a pollution-free and healthy living environment.

In summary, the lesson learnt from the unintentional natural experiment conducted on air quality in Singapore during the CB period is that the control of O_3 in urban environments is a challenging issue due to its complex formation in the atmosphere, with contributions from multiple precursors and sources. O_3 levels depend on background atmospheric conditions as well as emissions of its precursors. Therefore, full consideration of both prevailing meteorological and atmospheric chemistry conditions is critical in designing an effective O_3 control strategy. In addition, it is important to encourage more people to use public transport and/or switch from personal motorised transport to active mobility such as cycling and walking so that air quality benefits realised during the CB period can still be sustained over a long-term.

Overall, air quality studies conducted worldwide during the COVID-19 control measures period in 2020 enhanced our scientific understanding of complex and multi-faceted air pollution-related issues, which can lead to new policy interventions to contribute to healthy living in cities. Industrial activities, power plants and on-road vehicles are important sources of urban air pollution. Controlling emissions of air pollutants from these sources is key when control measures are eased. In this context, it is important for air quality scientists and policymakers to work together so that the scientific lessons learnt from air quality observations worldwide during the COVID-19 control measures period can be translated into effective air pollution control actions.

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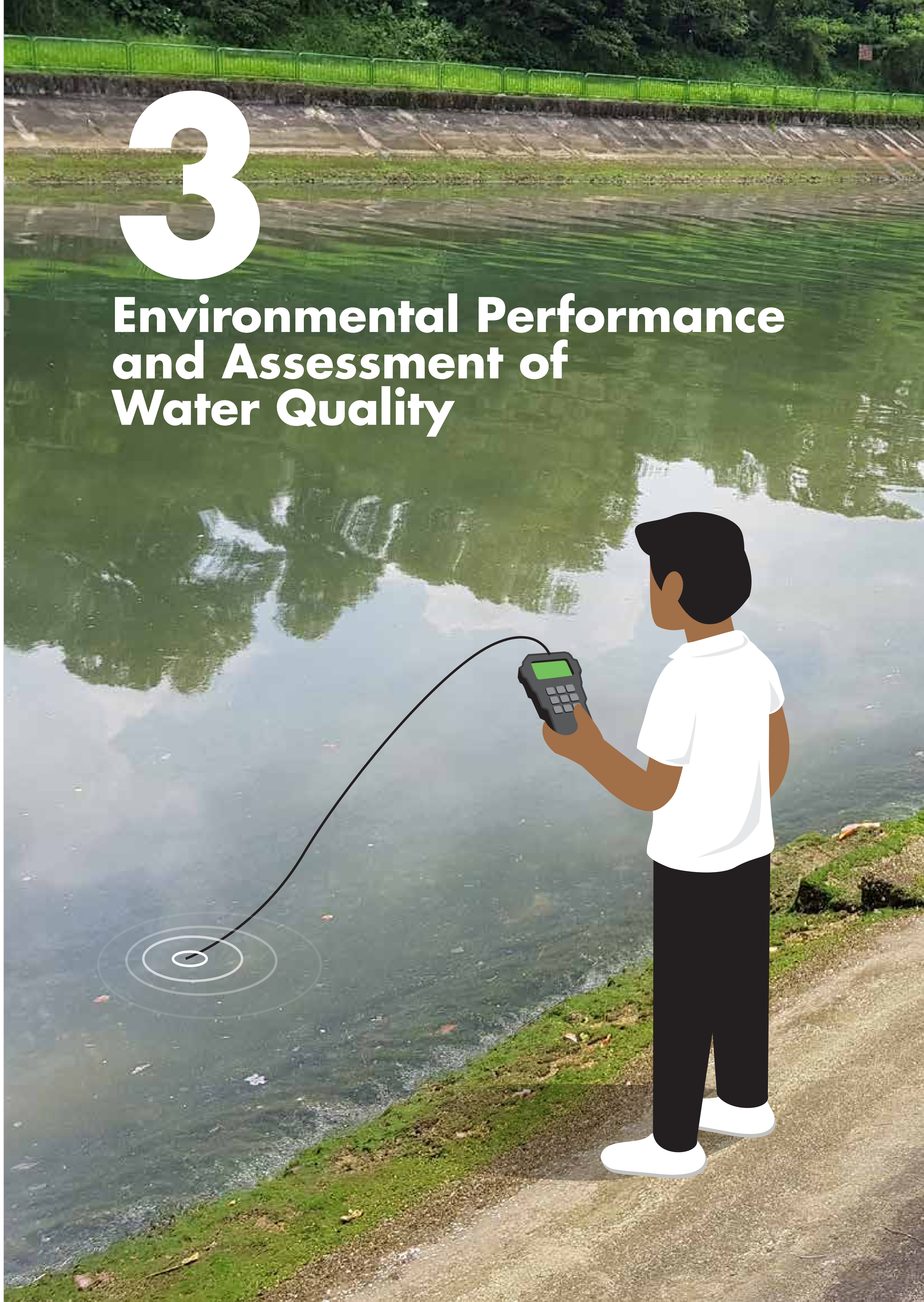
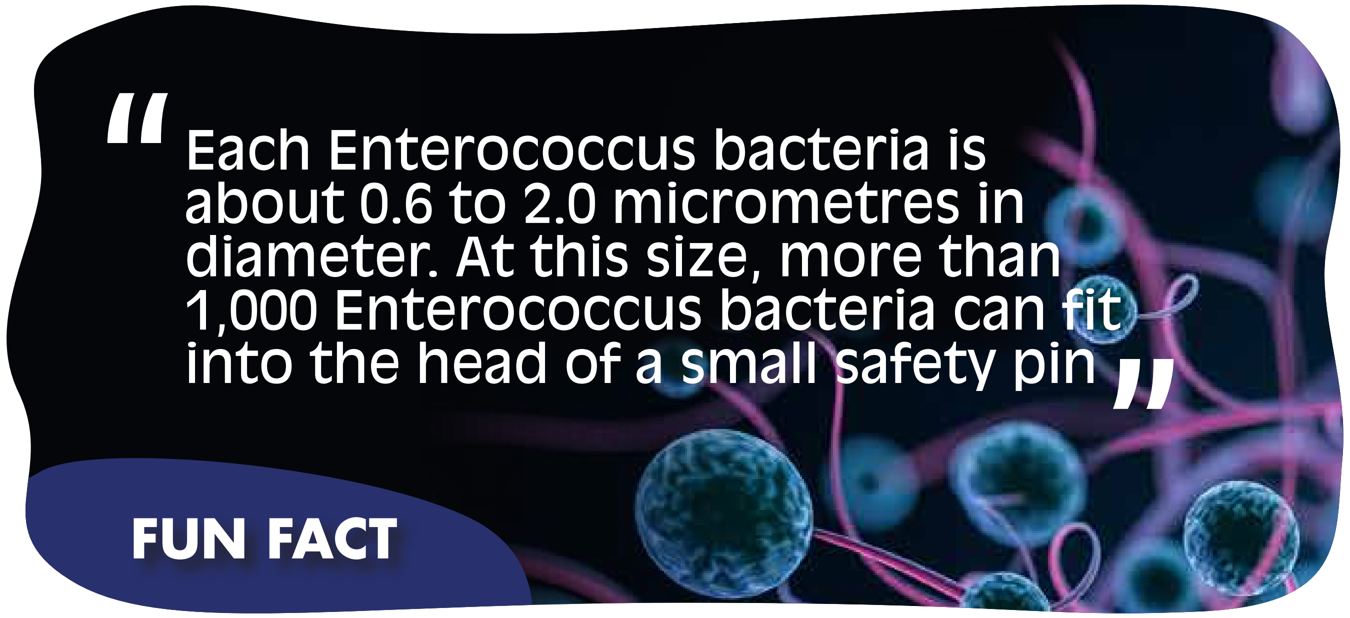


3 Environmental Performance and Assessment of Water Quality



SUSTAINING CLEAN WATERS

The National Environment Agency (NEA) monitors the water quality of various inland water bodies, coastal areas, and recreational beaches[1]. Through a combination of online continuous monitoring sensors and manual water sampling and analysis monitoring programmes, NEA identifies abnormalities in the water quality, track water quality impacted by pollution incidences like algal bloom and chemical spills and assess the effectiveness of upstream pollution controls in sustaining our clean waters.

INLAND AND COASTAL WATER MONITORING

The inland water monitoring programme comprises 74 sampling locations in water catchment areas (flow into reservoirs) and non-catchment (flow out to sea) areas, with sampling carried out on fortnightly to quarterly basis. Water samples are analysed for a range of physical, chemical, biological and microbiological parameters, and benchmarked against international standards.

Similarly, NEA has a coastal water monitoring programme along both the Straits of Singapore and Straits of Johor. Water samples are collected regularly at 43 sampling points and analysed for a range of physical, chemical, biological, and microbiological parameters.

In addition to the manual sampling of coastal water samples, NEA has a network of near real-time, continuous water quality monitoring system located in the Singapore waters. Commissioned in 2014, the monitoring system comprises 8 buoy-based monitoring stations with sensors for 15 key water quality parameters such as temperature, salinity, pH, dissolved oxygen, chlorophyll-a, turbidity. The continuous monitoring of coastal waters enables NEA to closely track water quality changes during pollution incidents.

RECREATIONAL BEACH MONITORING

Closer to our shoreline, NEA monitors the water quality of 7 popular recreational beaches including Sentosa Island, Seletar Island, Sembawang Park, Changi, East Coast Park, Pasir Ris, and Punggol, on a weekly basis. Water samples are tested for Enterococcus levels, an indicator of faecal pollution, to check for compliance with the WHO recreational water quality guidelines for primary contact water activities such as swimming.

In Oct 2020, NEA introduced a Short-term Beach Water Quality Information System (BSWI) which provides information on weekly assessment of water quality at the 7 beaches. The BSWI, accompanied by advisories according to the water quality bandings, allows beach goers to make informed decisions when engaging in primary contact activities at these beaches in the short-term. The BSWI can be found at https://www.nea.gov.sg/beach-water-quality. Apart from the weekly beach water quality information, the water quality of these beaches is graded annually to determine the overall performance of the water quality.

INLAND WATERS

CATCHMENT WATERS

Assessment of 2020 Performance

In 2020, the monthly mean of all the catchment water samples were within the NEA guidelines for Total Suspended Solids (TSS), Dissolved Oxygen (DO) and Biochemical Oxygen Demand (BOD) with the exception of BOD in Dec 2020. This could be attributed to intense episodes of rain throughout the Nov to Dec period in 2020. The prolonged and heavy rainfall could have resulted in a washdown of soil and other land-based pollutants, which in turn increased the amount of organic material entering the waterbodies. Hence, resulting in a higher amount of oxygen consumed by the organic material (i.e. higher BOD levels) in the waterbodies.

Assessment of Long-Term Performance

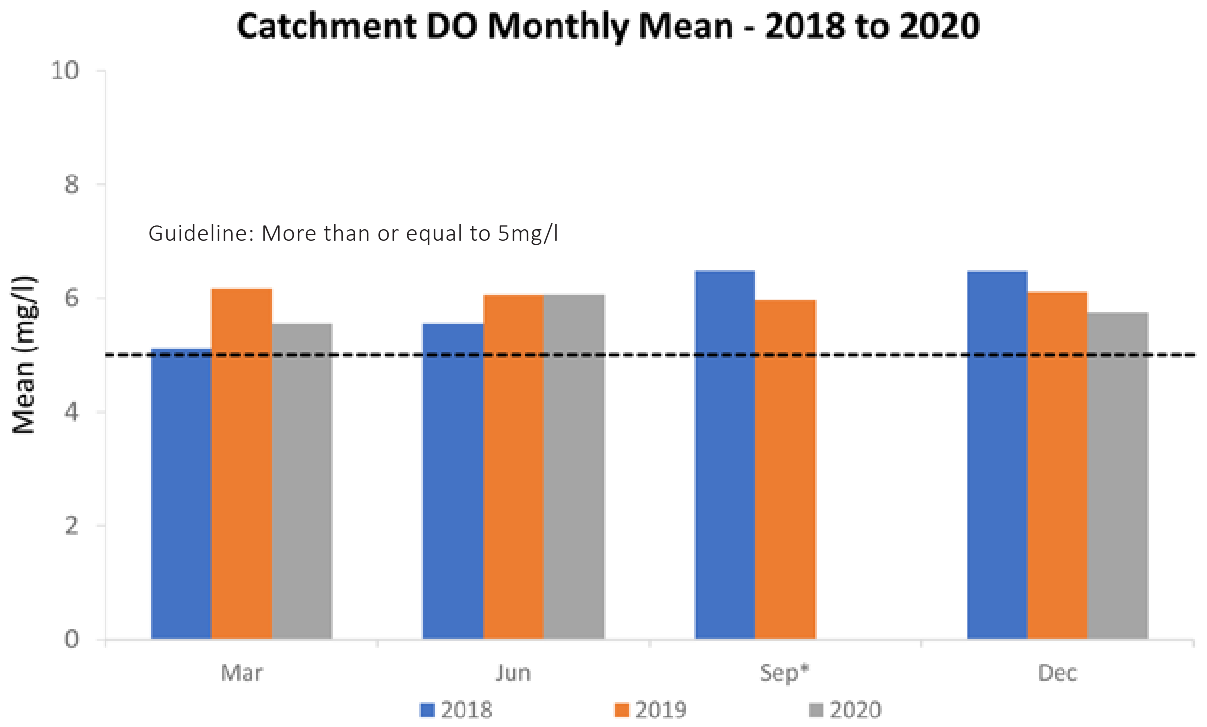
Over the last 10 years, TSS and BOD levels have remained within the NEA guidelines for catchment waters. Dissolved Oxygen (DO) levels in catchment waters however showed a decline from 2015 to 2017 with improvements observed subsequently in the recent 3 years. The decline in DO performance coincided with the El Nino weather, where hotter conditions and lesser rainfall were experienced. At higher water temperatures, waterbodies tend to hold less dissolved oxygen.

Inland water body at Bishan Park

[1] PUB monitors the water quality of reservoirs, which is one of the four sources (i.e. local catchment) or National Taps for the supply of portable drinking water.

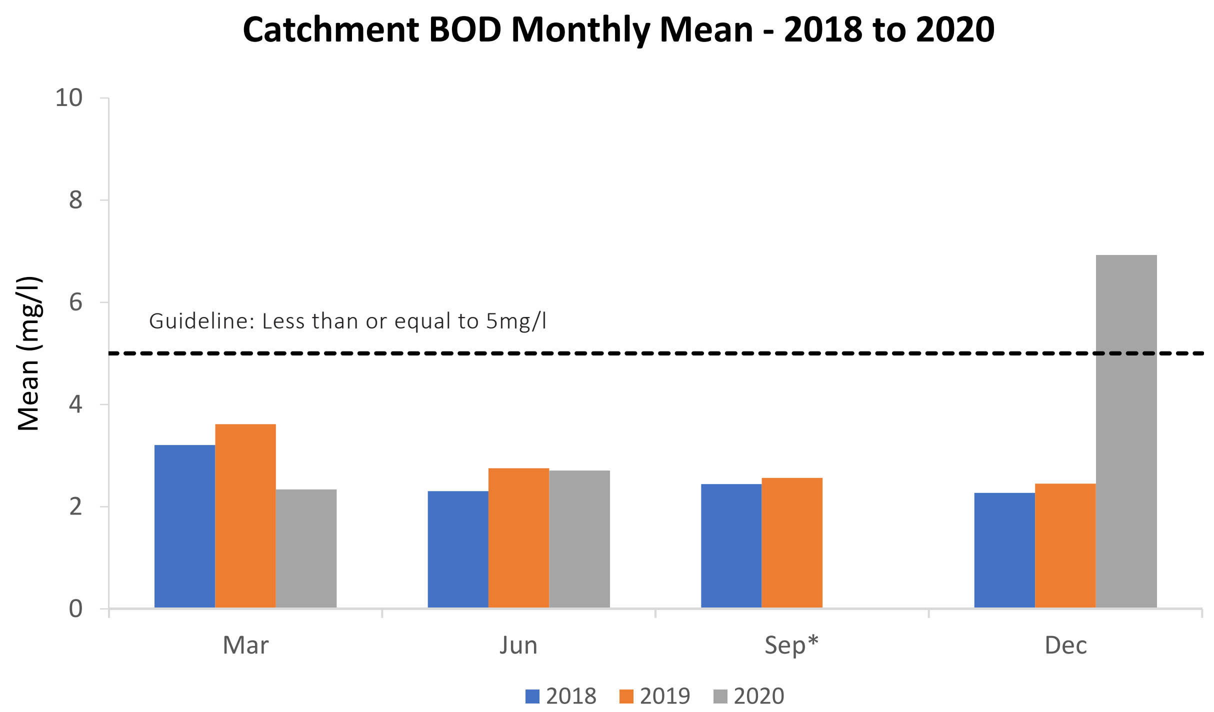
[2] NEA's guidelines for dissolved oxygen, biochemical oxygen demand, and total suspended solids in catchment waters are aligned with the 2005 ASEAN Strategic Plan of Action on Water Resources Management of ≥5 mg/l, ≤5 mg/l and ≤50 mg/l, respectively.

MONTHLY TRENDS (2018 - 2020)



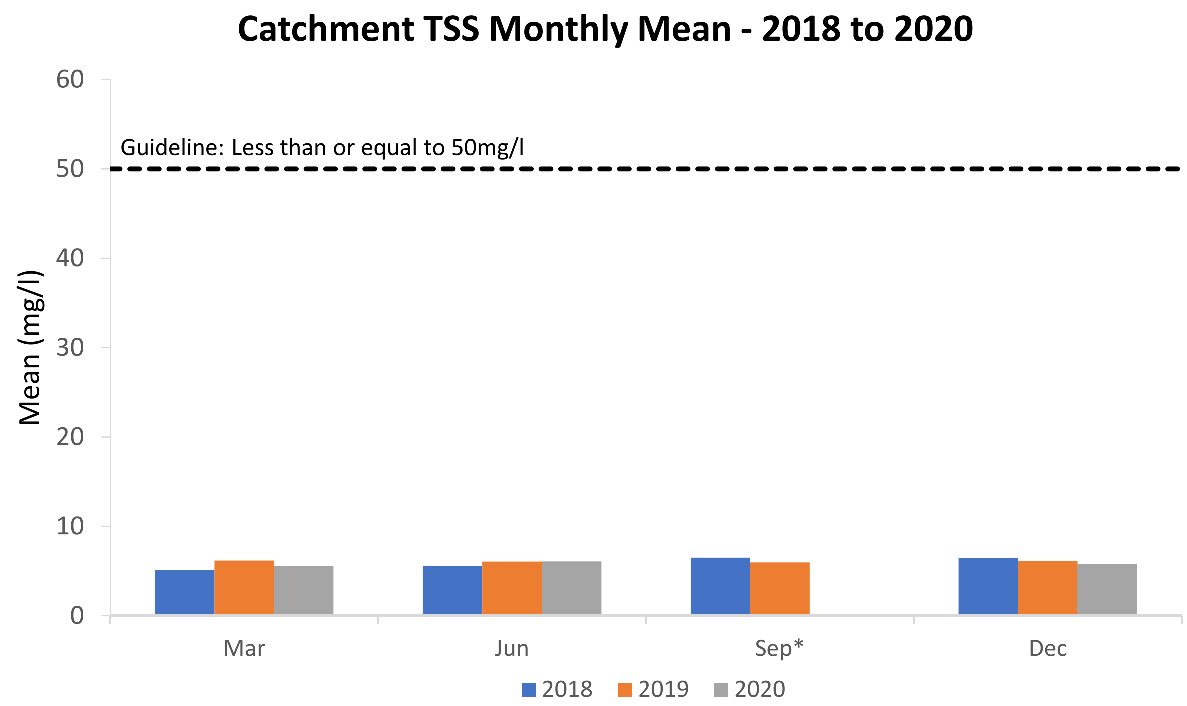
*Sampling in Sep 2020 was not completed due to Covid-19 related constraints

Figure 1. *Catchment waters dissolved oxygen monthly mean from 2018 to 2020*



*Sampling in Sep 2020 was not completed due to Covid-19 related constraints

Figure 2. *Catchment waters biochemical oxygen demand monthly mean from 2018 to 2020*



*Sampling in Sep 2020 was not completed due to Covid-19 related constraints

Figure 3. *Catchment waters total suspended solids monthly mean from 2018 to 2020*

ANNUAL TRENDS (2011 – 2020)

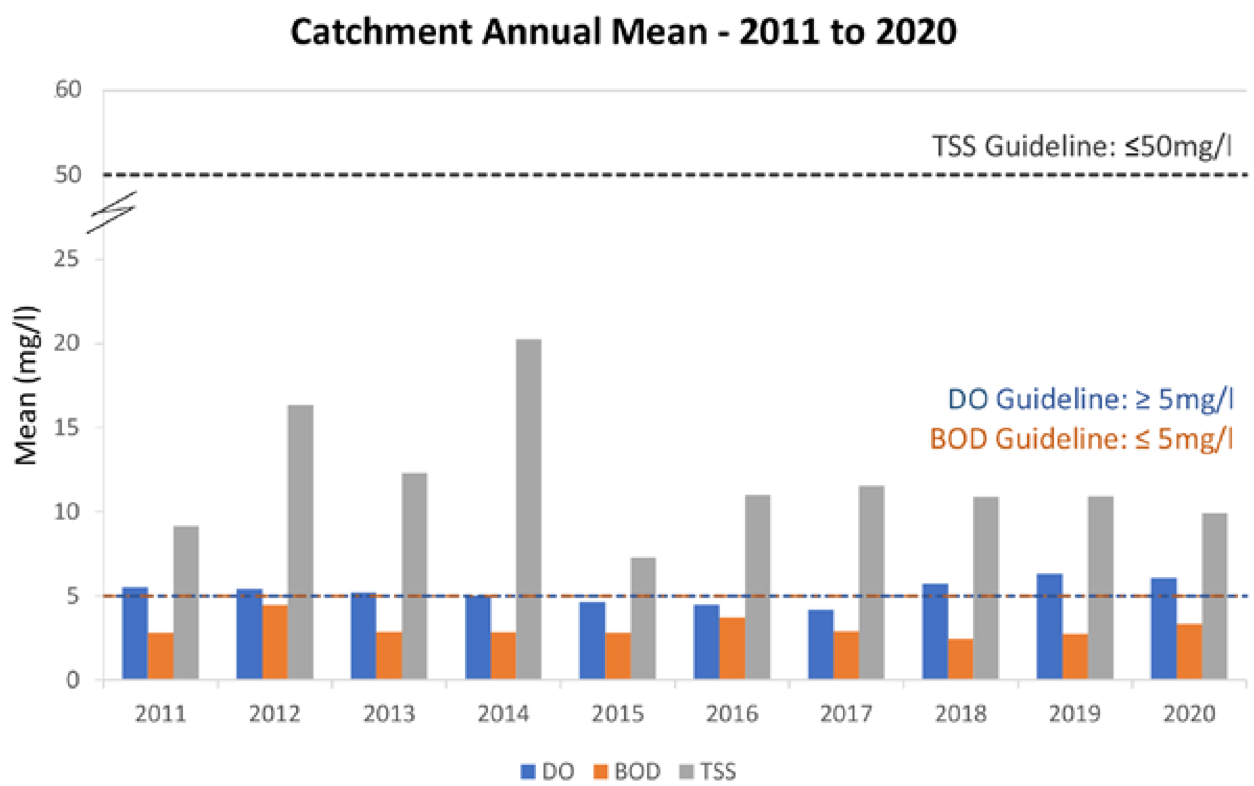


Figure 4. *Catchment waters annual mean from 2011 to 2020*

Sungei Api Api

NON-CATCHMENT WATERS

Assessment of 2020 Performance

In 2020, the DO and TSS in non-catchment rivers and streams were within the NEA guidelines[3] for all the samples, as was the case for the 3 years since 2018.

Similar to that for catchment waters, the BOD were within the guidelines in 2020 with the exception of Dec 2020. This could similarly be attributed to intense episodes of rain throughout the Nov to Dec period.

Assessment of Long-Term Performance

TSS, DO and BOD annual mean levels have remained within the NEA guidelines over the last 10 years.

[3] NEA's guidelines for dissolved oxygen, biochemical oxygen demand, and total suspended solids in non-catchment waters are aligned with the ASEAN 2005 ASEAN Strategic Plan of Action on Water Resources Management of ≥3 mg/l, ≤10mg/l and ≤300mg/l, respectively.

MONTHLY TRENDS (2018 – 2020)

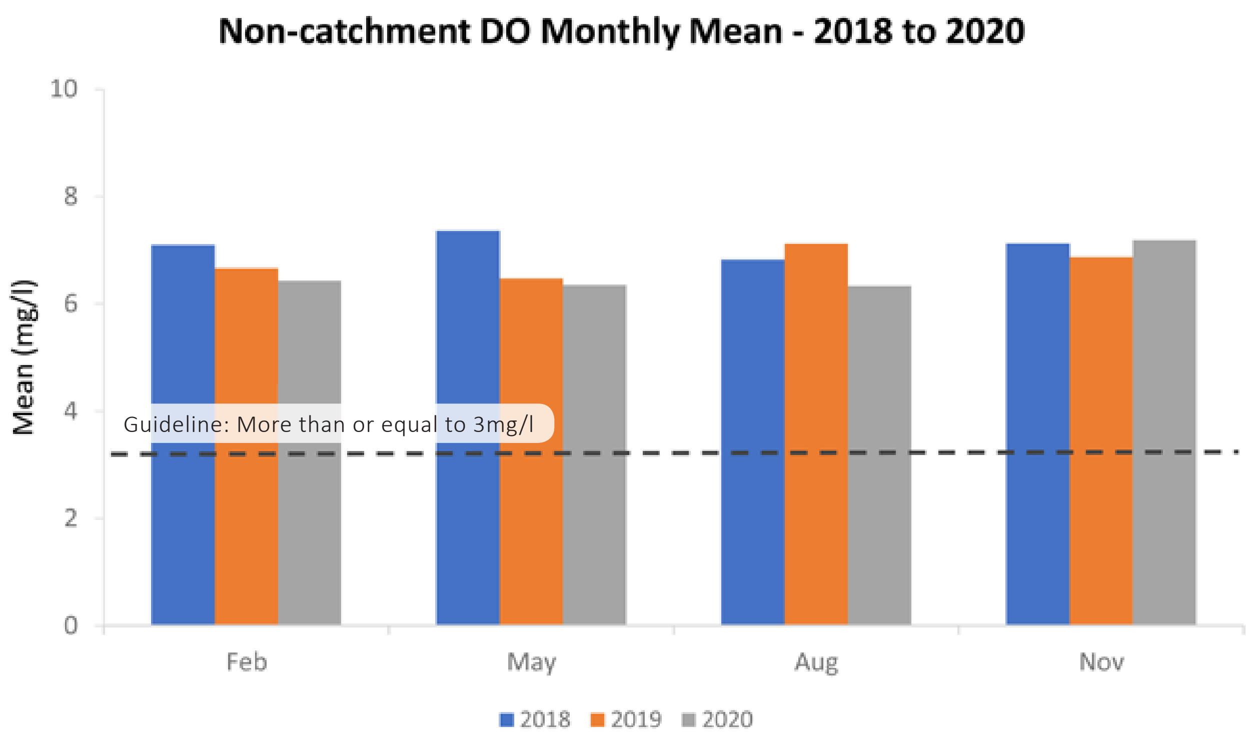


Figure 5. *Non-catchment waters dissolved oxygen monthly mean from 2018 to 2020*

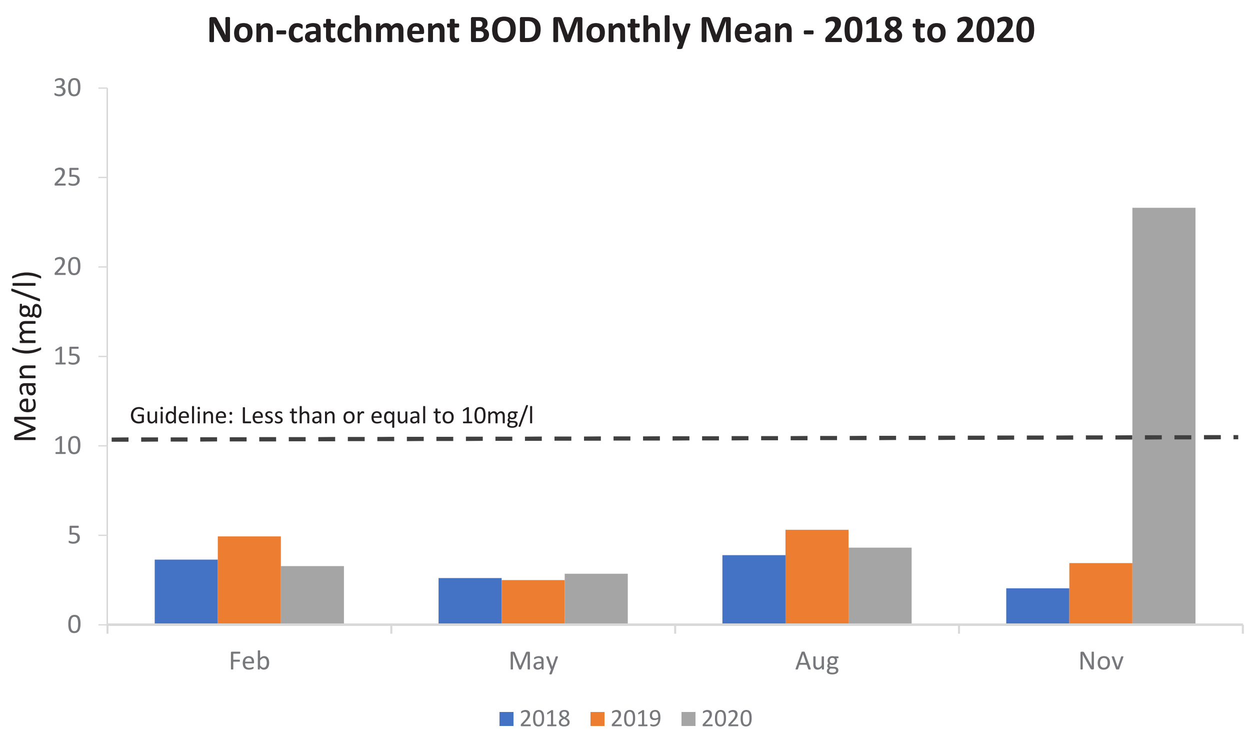


Figure 6. *Non-catchment waters biochemical oxygen demand monthly mean from 2018 to 2020*

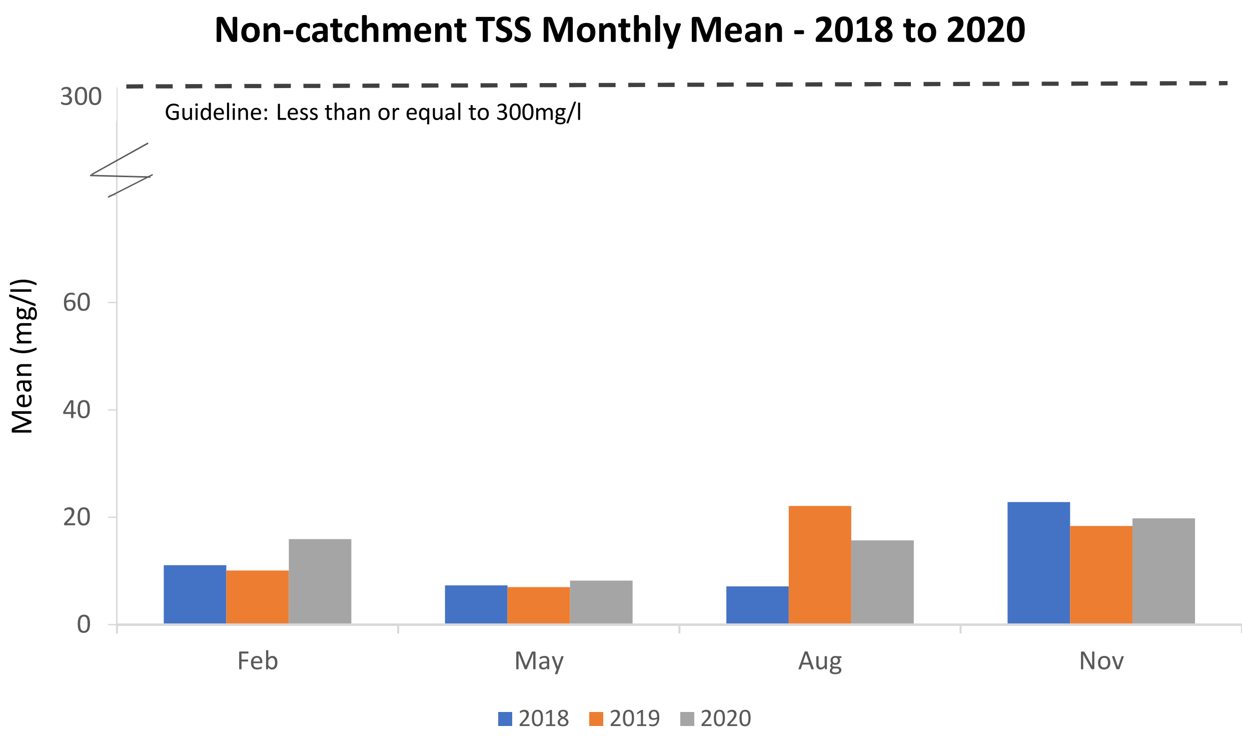


Figure 7. *Non-catchment waters total suspended solids monthly mean from 2018 to 2020*

ANNUAL TRENDS (2011 – 2020)

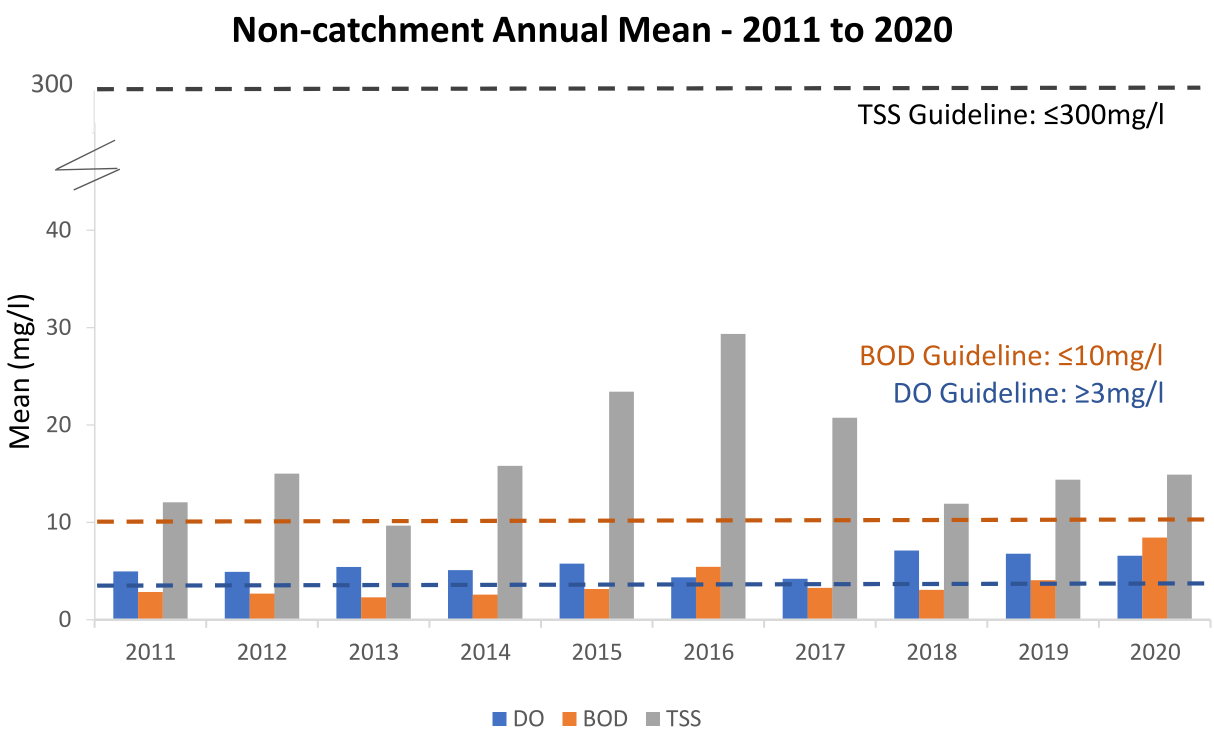


Figure 8. *Non-catchment waters annual mean from 2011 to 2020*

COASTAL WATERS

Assessment of 2020 Performance

DO in coastal waters met the water quality guidelines of 4mg/l for all months of 2020. Water quality did not meet the enterococcus guideline of 200 counts per 100ml in May 2020. The monthly mean enterococcus levels fluctuated over the past 3 years along Straits of Johor (SOJ) West, SOJ East and Straits of Singapore (SOS). This could be attributed to various possible reasons, such as run-offs or discharges from inland waterways, sewer leakages, shipping discharges, or water current movements.

Assessment of Long-Term Performance

DO and enterococcus annual mean levels remained relatively stable over the past 10 years.

Officer taking water quality reading during coastal water sampling

MONTHLY TRENDS (2018 – 2020)

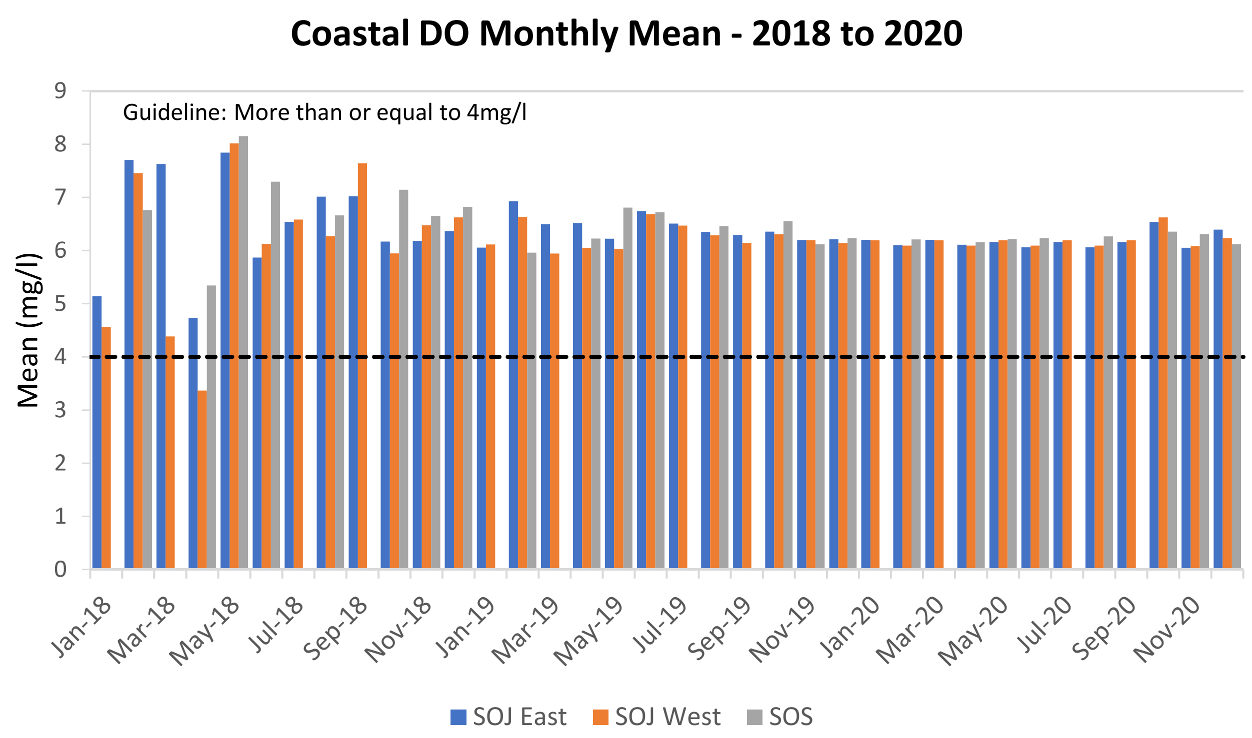


Figure 9. *Coastal waters dissolved oxygen monthly mean from 2018 to 2020*

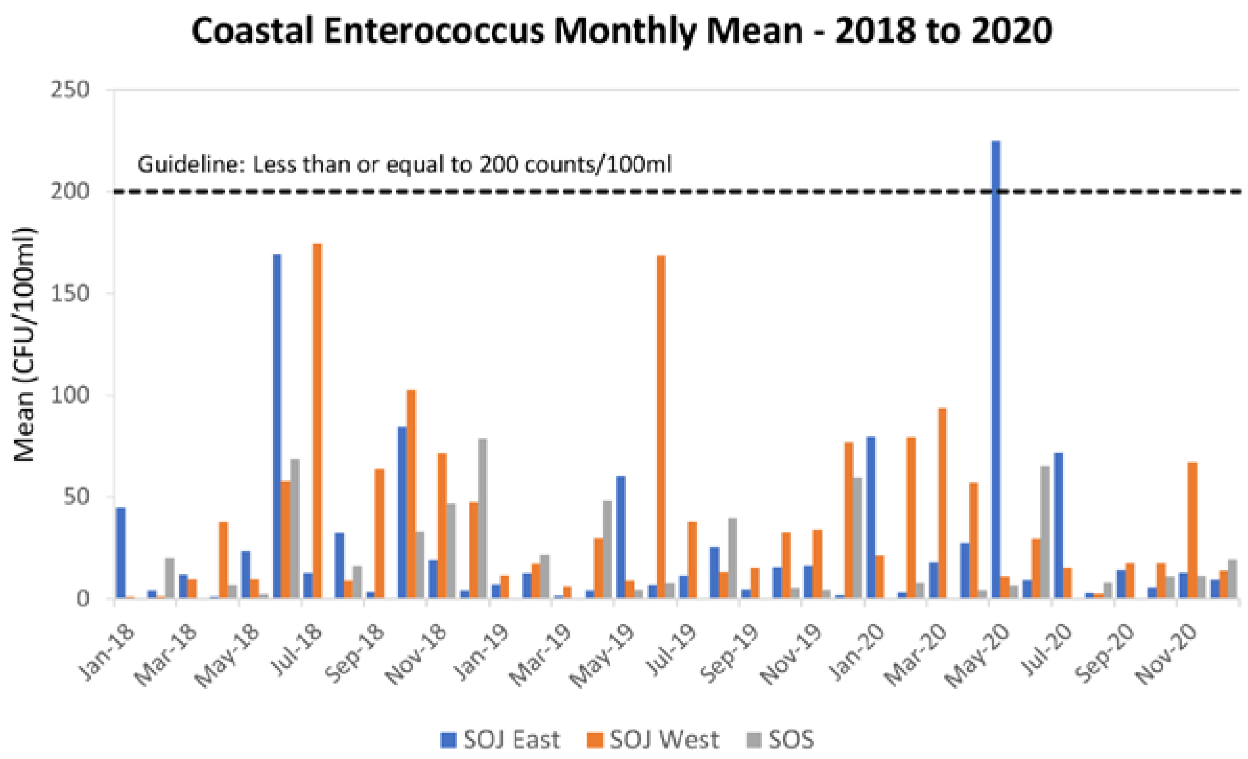


Figure 10. *Coastal waters Enterococcus counts monthly mean from 2018 to 2020*

ANNUAL TRENDS (2011 – 2020)

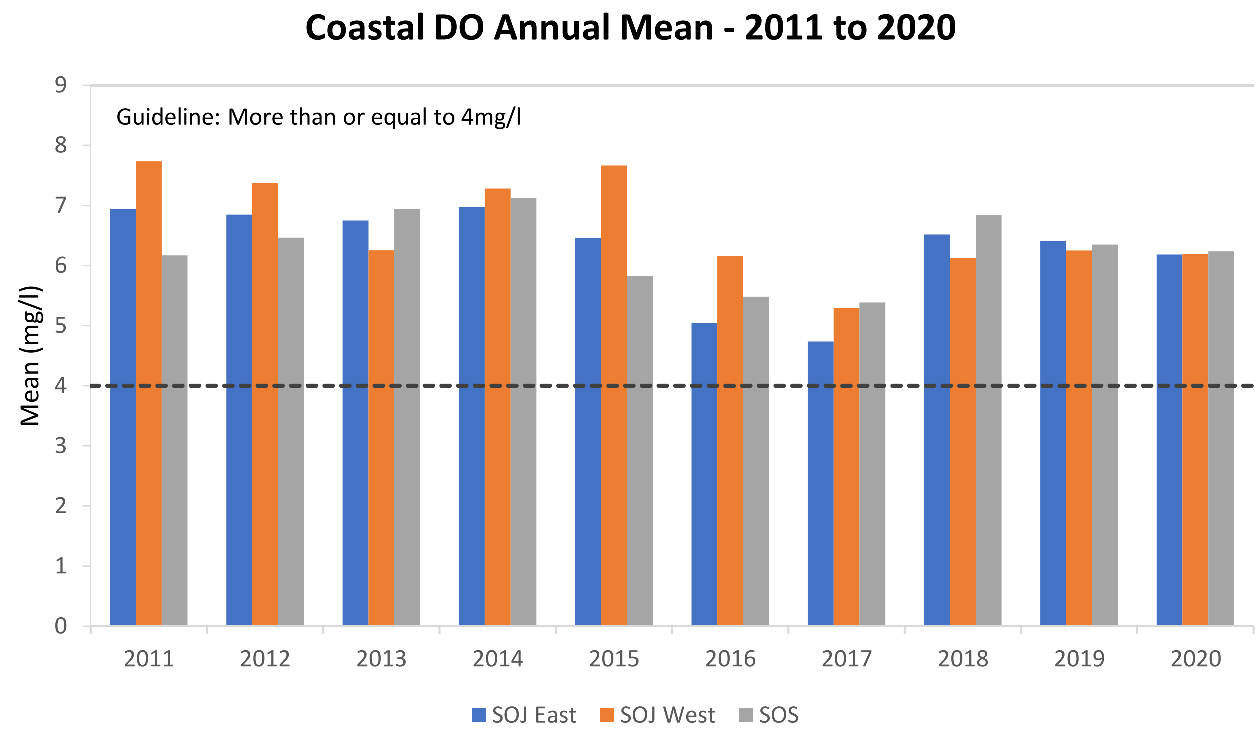


Figure 11. *Coastal waters dissolved oxygen annual mean from 2011 to 2020*

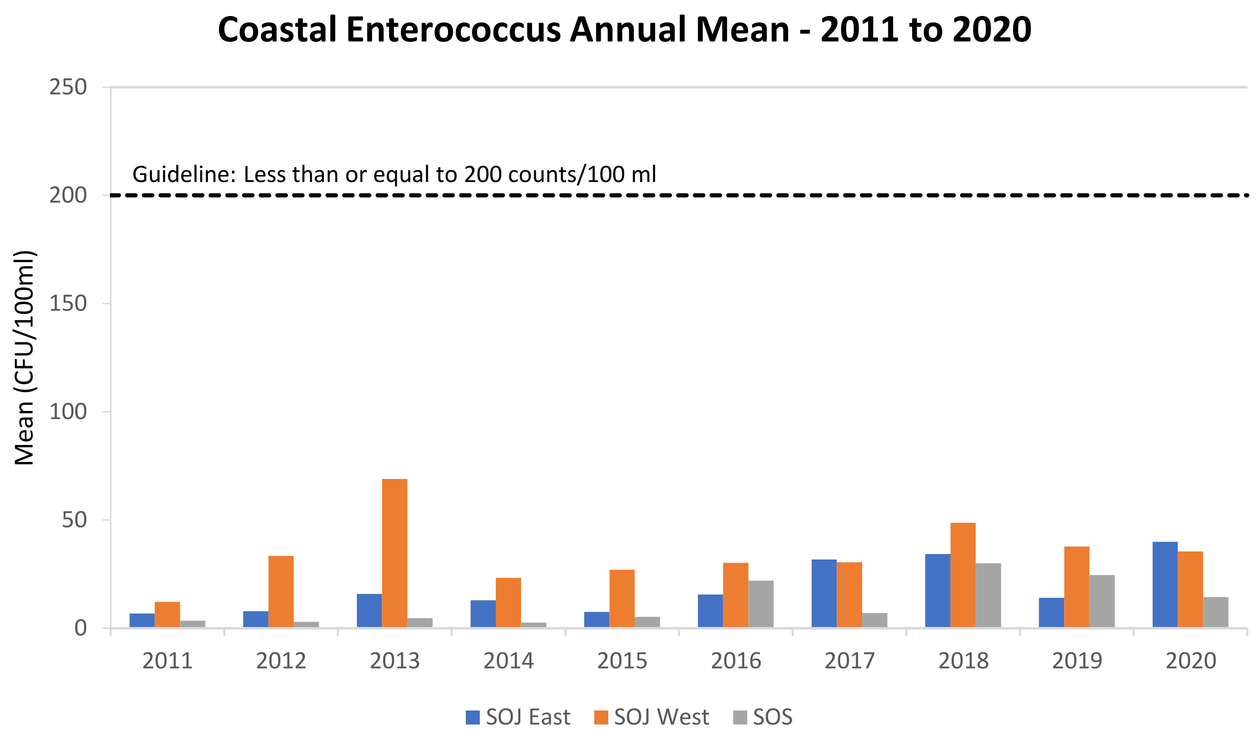


Figure 12. *Coastal waters Enterococcus counts annual mean from 2011 to 2020*

RECREATIONAL BEACHES

Assessment of 2020 Performance

All seven of the monitored recreational beaches achieved a “Good” banding for 2020, based on NEA’s recreational water quality guidelines[4], and were suitable for primary contact recreational activities.

Assessment of Long-Term Performance

Although the Enterococcus levels at the recreational beaches have shown a slight increasing trend over the last 10 years, the levels remain within the guidelines and have improved for some of the beaches in the most recent 3 years. Possible sources of faecal contamination affecting beaches include runoffs from land-based activities entering the coastal waters, sewer leakages, discharges from passing or moored ships, among others.

PUB has an ongoing programme for sewer rehabilitation, with systematic checks and repairs to public sewers across Singapore. NEA will continue to monitor the water quality at the popular recreational beaches and work with other agencies to minimise contamination from possible sources.

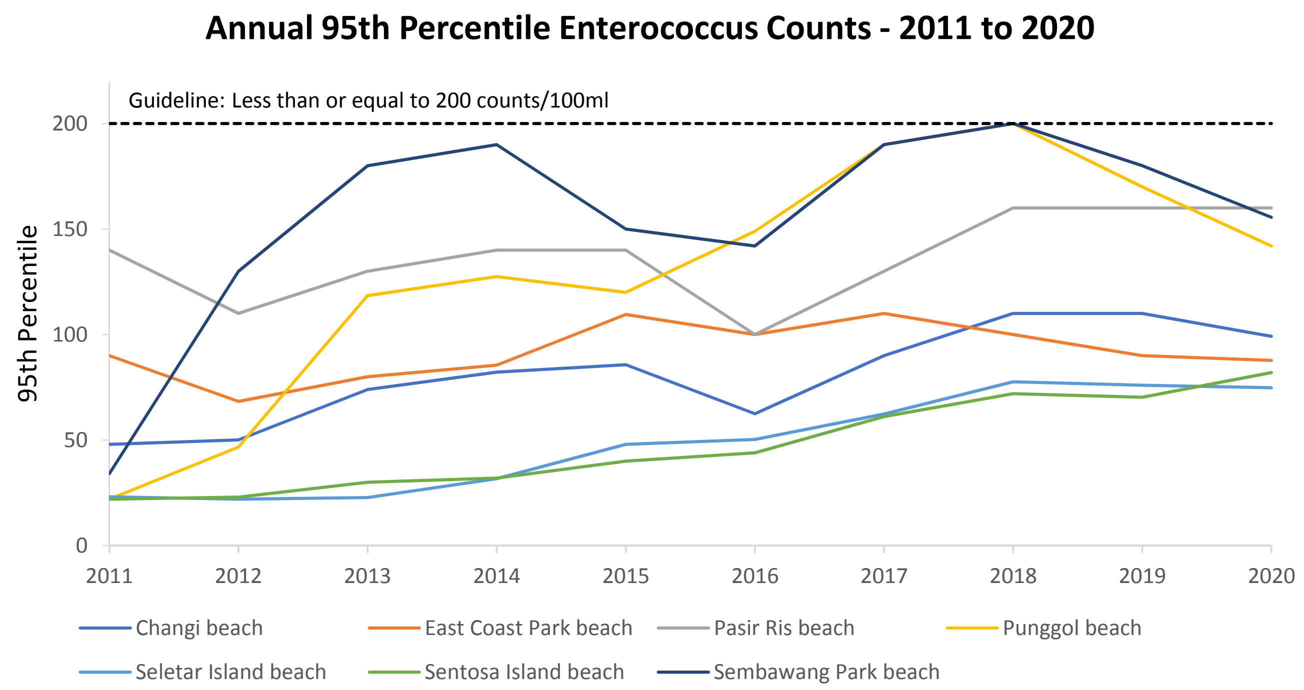


Figure 13. *Annual 95th Percentile Enterococcus Counts from 2011 to 2020*

[4] Based on the WHO Water Quality Guidelines for recreational use. Under the guidelines, primary contact activity is only allowed when the 95th percentile enterococcus bacteria counts of the recreational beach water do not exceed 200counts/100 ml.

ANNEX: NEA’S GUIDELINES AND PARAMETERS

Our monitoring programmes cover a range of physical, chemical, and bacteriological parameters. This report highlights key parameters monitored, such as dissolved oxygen (DO), total suspended solids (TSS), biochemical oxygen demand (BOD), and enterococcus (EC).

GUIDELINES FOR INLAND WATERS

Inland water quality is assessed based on guideline values from 2005 ASEAN Strategic Plan of Action on Water Resources Management for Class I and Class IV rivers in Table 1. The guidelines for catchment waters are more stringent so as to ensure that the water is suitable for potable use as well.

Table 1. *ASEAN Strategic Plan of Action on Water Resources Management Standards*

Parameter	Class I	Class IV
Dissolved oxygen (mg/l)	5	3
Total suspended solids (mg/l)	50	300
Biochemical oxygen demand (mg/l)	5	10

Dissolved Oxygen

Dissolved oxygen (DO) is a measure of the amount of oxygen dissolved in water. This indicates how much oxygen is available to living aquatic organisms and dictates the amount of aquatic life that can be supported, as aquatic organisms require dissolved oxygen for respiration. At low levels of DO, aquatic life may not be able to survive. DO is an indicator of ecological health, ensuring that our waters can continue to support aquatic life.

Total Suspended Solids

Total suspended solids (TSS) is an indicator of water clarity, which dictates photosynthesis rates and the survival of aquatic plants or benthic (i.e. organisms living on the riverbed) organisms in the water. When there is higher amount of suspended solids in water, water clarity is reduced and photosynthesis rates are inhibited as sunlight is blocked. This would then decrease the survival of aquatic plants and other organisms in the water. TSS is an indicator of ecological health, ensuring that our waters can continue to support aquatic life.

Biochemical Oxygen Demand

Biochemical oxygen demand (BOD) indicates the amount of oxygen used by aerobic microorganisms when decomposing organic matter in the water, which signifies the degree of organic pollution in water. Elevated BOD could indicate contamination from effluent or wastewater discharges.

GUIDELINES FOR COASTAL WATERS

The ASEAN Marine Water Quality Criteria (AMWQC) for DO of 4mg/l is used as a reference to benchmark our coastal water quality for aquatic life protection. Enterococcus level in coastal water is benchmarked against World Health Organisation (WHO)'s recreational water quality guidelines, which is 200 counts/100 ml, for public health protection.

Enterococcus

Enterococcus is a type of bacteria normally found in the faeces of humans and warm-blooded animals. It is widely used to indicate the level of faecal contamination in water. Faecal contamination in water can cause negative health impacts such as gastrointestinal and respiratory infections.

4

Use of Low-cost Sensors for High Spatial Resolution Air Quality Monitoring

Figure 1. **LEFT:** *Low-cost Sensor* **RIGHT:** *Air Quality Monitoring Station*

The use of low-cost sensors in air quality monitoring is becoming increasingly popular, as they are portable and cheaper in both acquisition and operating cost. Furthermore, with much smaller footprints compared to our typical air quality monitoring stations which are equipped with the specialised scientific analysers based on US Environmental Protection Agency (EPA) reference methods, it is easier to find suitable locations to deploy them. While there are trade-offs with regards to the robustness, calibration requirements and accuracy of low-cost sensors compared to analysers at the national reporting stations (Mao et al., 2019), the low cost and portability of the sensors make it possible to obtain air quality measurements in more locations, such as along roadsides, in areas where there is high pedestrian activity, or near sources of pollution that may not have space to site an air quality monitoring station. For instance, in London and Paris, over a hundred low-cost sensors have been deployed as additional monitoring points or as part of studies to better understand air quality. Furthermore, in the US, the rapid adoption of low-cost sensor networks over the past decade has prompted the US EPA to establish guidelines on evaluation procedures to determine the accuracy of such sensors.

FUN FACT

"The size of one ambient air monitoring station is equivalent to the size of more than 3000 low-cost air quality sensors"

This article discusses NEA's trials with low-cost sensors so far, and the potential of data from the deployment of such sensors.

BACKGROUND

NEA has been conducting field trials of low-cost sensors capable of measuring both fine particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2). The measurement of $PM_{2.5}$ is carried out via laser light scattering technology, which passes laser beams through an air sample, causing large particles to scatter light at smaller angles relative to the laser beam and small particles to scatter light at larger angles. Particle sizes are then determined from the measured variation in the intensity of scattered light with reference to the scattering angles. The measurement of NO_2 is carried out via electrochemical cell technology which uses chemical reactions to generate a current when NO_2 gas comes into contact with chemicals within the sensor. The magnitude of this current is proportional to the concentration of the gas.

After a study to assess the reliability and accuracy of low-cost sensors under local environmental conditions in 2017/2018, a field trial was conducted to further evaluate the performance of a network of such sensors.

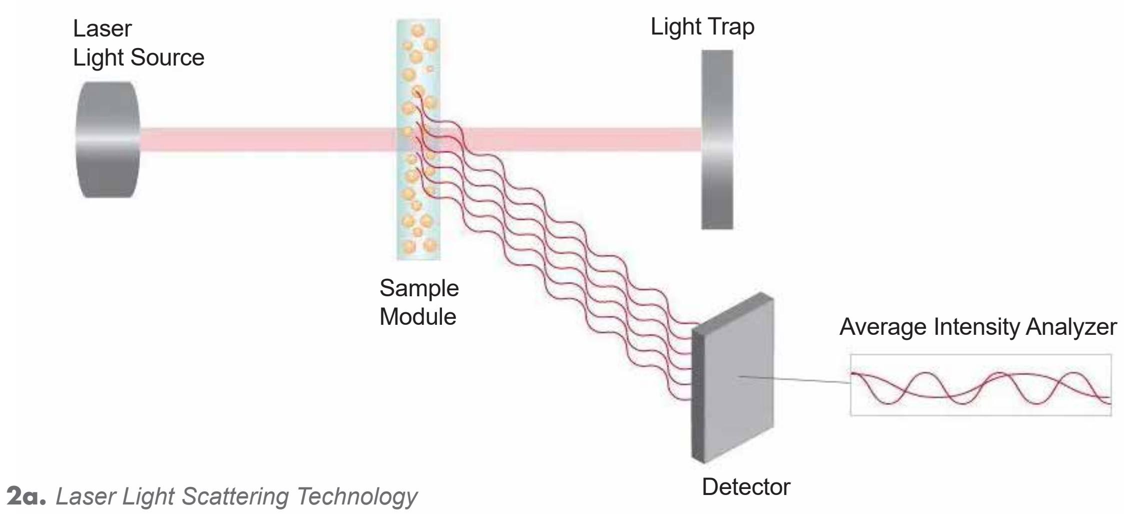


Figure 2a. *Laser Light Scattering Technology*

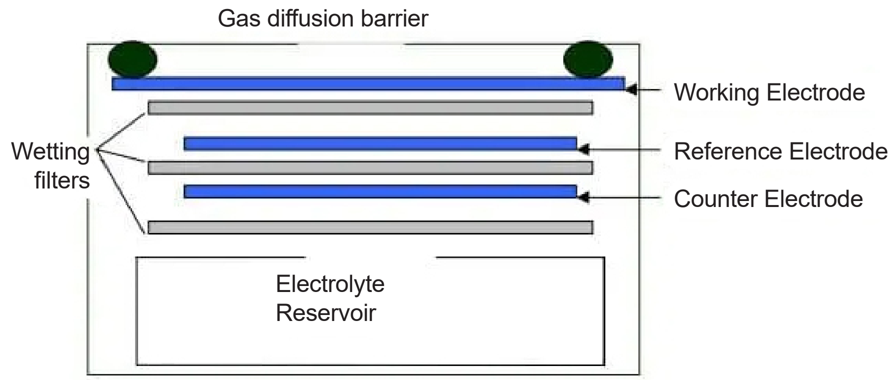


Figure 2b. *Electrochemical Cell Technology*

FIELD TRIAL OF LOW-COST SENSOR NETWORK AT A RESIDENTIAL ESTATE

A network of 28 low-cost sensors were deployed across a residential estate to assess the performance of the sensors, validate the air quality data measured by the sensors, and assess the potential to map air quality at high spatial resolution at a localised area. All the low-cost sensors were co-located with a NEA air quality monitoring station for initial calibration, prior to their deployment. The network of sensors were placed at selected lampposts across the estate to understand the air quality and air dispersion within the estate.

Figure 3a. *Low-cost Sensor at Overhead Bridge*

Figure 3b. *Low-cost Sensor on Lamppost near Basketball Court in Residential Area*

The sensors were also deployed at varying floors of a public housing block of flats to study the vertical dispersion of pollutants at different heights. Such monitoring data could also provide insights into the influences of weather conditions such as wind speed, wind direction, and more, on air pollutant levels at varying heights.

PERFORMANCE OF LOW-COST SENSORS AND KEY FINDINGS

SENSOR PERFORMANCE

The operational performance of the sensors has been satisfactory thus far with excellent solar charging of batteries and cellular signal strength, and data completeness of close to 100%.

In terms of accuracy of the sensors, the $PM_{2.5}$ sensors achieved a coefficient of determination (R^2) of 0.73 and a Root Mean Square Error (RMSE) of 3.14 μg/m^3, when compared with the measurement of the nearest air quality monitoring station. This meets the US EPA's recommended guideline target values of $R^2 \geq 0.7$ and RMSE ≤ 7 μg/m^3 for the accuracy of such $PM_{2.5}$ sensors.

The NO_2 sensors however did not perform as well, with R^2 and RMSE of 0.42 and 11.0 μg/m^3 respectively. Further improvements will have to be explored for data from the NO_2 sensor to meet accuracy requirements.

KEY FINDINGS ON DISPERSION OF AIR POLLUTANTS

Measurements from the low-cost sensors showed that the $PM_{2.5}$ of locations next to an expressway over the six-month trial were within the WHO AQG (2005) of 25 μg/m^3.

Looking at the diurnal trends, it was found that the $PM_{2.5}$ levels showed an increase from 12 midnight and continued upwards throughout the night and peaking at 7am before dipping for the rest of the morning. In addition, the ground level $PM_{2.5}$ levels were consistently higher than that at the 12th floor during the night. This was reversed during the day with the ground level $PM_{2.5}$ being lower. These observed trends are likely influenced by temperature, wind, and atmospheric conditions. During the day, solar radiation heats the ground surface, causing the warm surface air to rise rapidly. This convection process promotes vertical atmospheric mixing and as a result, particulate matter released near the ground during the day has a larger probability of being dispersed throughout the atmosphere, thereby leading to lower $PM_{2.5}$ concentrations at ground level. In the evening, this relationship reverses, with the loss of solar radiation promoting cooling of the ground surface. As cold air is denser than warm air, there is less potential for vertical mixing and therefore increased atmospheric stability. Coupled with generally lower wind speeds during the night, higher $PM_{2.5}$ concentrations can be attributed to the accumulation of particulate matter near ground levels. This phenomenon is seen in the gradual downward trend in $PM_{2.5}$ concentrations between 7am to 12 noon.

The findings illustrated in this section demonstrate the potential usefulness of low-cost sensors to uncover insightful trends and phenomenon relating to air quality. This is attributed to their flexibility and relative ease of deployment to obtain high spatial (both vertical and horizontal) and temporal resolution of air quality data.

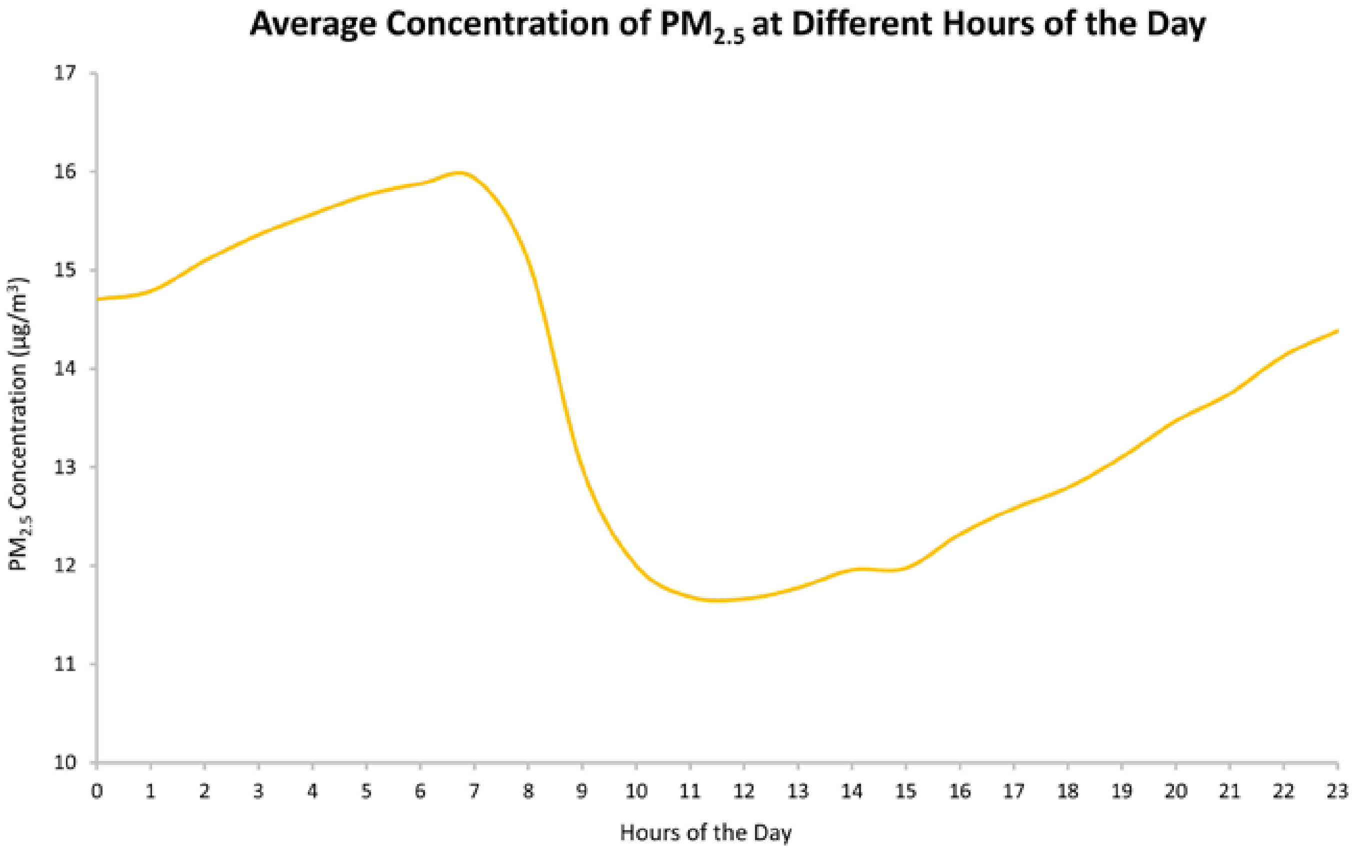


Figure 4. *Average Concentrations of $PM_{2.5}$ at Different Hours of the Day*

AIR DISPERSION MODEL

The low-cost sensor network is also equipped with a customised air dispersion model. The model integrates measurement data from the low-cost sensor with other data sources such as real-time meteorological data, traffic emissions, background concentration from nearby air monitoring station, among others, and is progressively refined as more data is collected. The dispersion model enables hourly air quality heat maps to be generated across the area covered by the low-cost sensors, providing a continuous coverage of air quality data within an area, instead of only discrete air quality data points from each individual sensor.

To assess the accuracy of the model output, a portable $PM_{2.5}$ analyser was deployed to validate the model output at four different locations within the modelling boundary for approximately one week at each location. The R^2 and RMSE between the model output and the portable $PM_{2.5}$ sensor ranged from 0.70 to 0.97 and 1.80 to 3.70 µg/m³ respectively. Taking the US EPA's recommended target values of $R^2 \geq 0.7$ and RMSE ≤ 7 µg/m³ for the accuracy of indicative $PM_{2.5}$ sensors as a reference, the validation result was found to be satisfactory as the recommended target values were met.

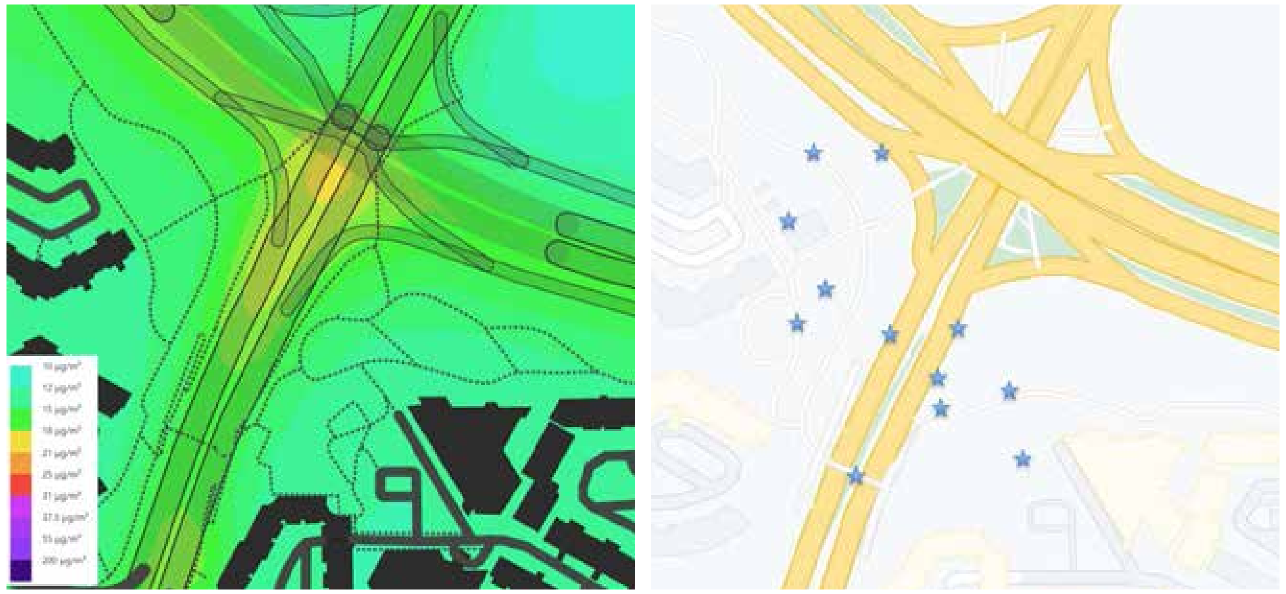


Figure 5. *Continuous Coverage of Air Quality Data vs Discrete Data Point from Individual Sensor*

In general, higher $PM_{2.5}$ were observed at traffic intersections. This is due to accumulation of particulate matter as vehicles frequently slow down or stop for a short period of time before accelerating to cross the intersections. Notwithstanding this phenomenon, the dispersion and dilution effects of ground level $PM_{2.5}$ levels from traffic emissions are found to be expeditious, as the $PM_{2.5}$ levels fall sharply with increasing distance from the intersection. $PM_{2.5}$ readings at developments near to the intersections were all within the WHO AQG (2005) of 25 µg/m³.

POTENTIAL FUTURE DEPLOYMENT AND USE OF LOW-COST SENSORS DATA

The data from the low-cost sensor network provide high spatial resolution air quality information and insights into how air pollutants disperse within an estate. Furthermore, leveraging on such sensors enable the development of more accurate and higher resolution models. Moving forward, the low-cost sensor network together with the air dispersion model could potentially be deployed at potential hotspots, like a major industrial facility for example, to check for the adequate dispersion of air pollutants.

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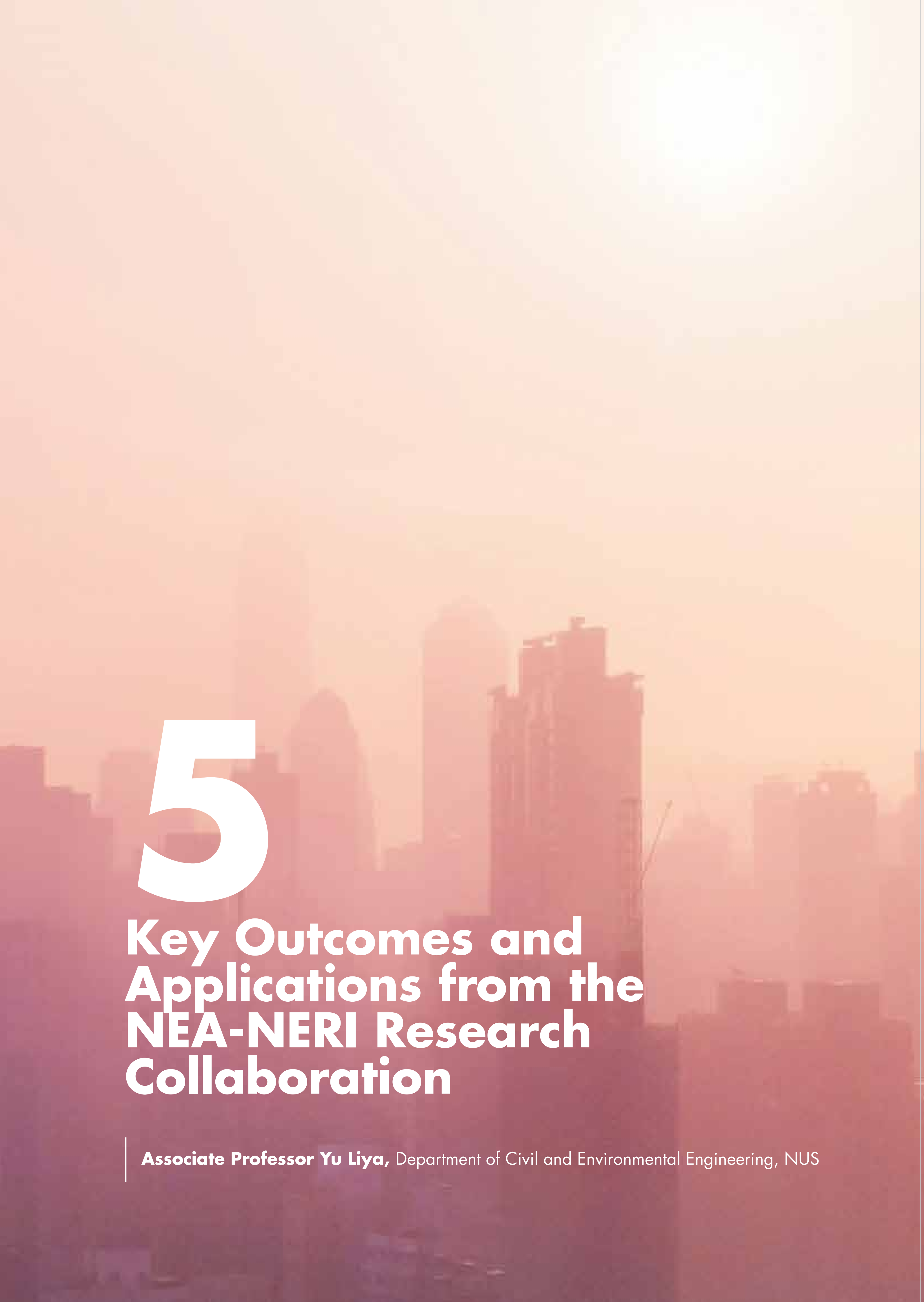
Electrochemical Sensor: https://www.aeroqual.com/challenges-electrochemical-no2-sensors-outdoor-air-monitoring



5

Key Outcomes and Applications from the NEA-NERI Research Collaboration

Associate Professor Yu Liya, Department of Civil and Environmental Engineering, NUS

BACKGROUND

Haze has been a long-standing issue in Singapore since the 1970s. Such incidents are often attributed to high concentrations of $PM_{2.5}$, a fine particulate commonly known to be generated from forest fires and vehicular emissions but can also be generated from various atmospheric processes and reactions. Being tiny in nature enables these particles to penetrate deep into the lungs and increase the risk of heart and lung illnesses. They are highly complex particles made up of numerous components (for example inorganic, organic, metals and more.) and thus in-depth research is vital in enhancing NEA's understanding of the approach to manage this complicated pollutant.

From 2015 to 2020, NEA embarked on a collaboration with NUS Environmental Research Institute (NERI) to study the characterization of $PM_{2.5}$ in Singapore. This partnership allowed NEA to leverage on the expertise of research scientists and utilise state-of-the-art specialized equipment to understand the components of $PM_{2.5}$. Over the study period, the NERI team conducted long term monitoring of $PM_{2.5}$ particulates at their monitoring site to investigate $PM_{2.5}$'s physical properties such as size, weight and number concentration, and chemical properties and composition.

This research provided insights on the characteristics and composition of the particulate matter in Singapore, as well as its likely pathways and sources. For instance, the study had found that organic carbon and sulphates were consistently the highest constituents of $PM_{2.5}$. Organic carbon can come from both anthropogenic and biogenic sources while sulphates are mainly generated from refineries and shipping (namely emissions of sulphur dioxide). These give insight into the quantity of emissions from various categories of emission sources.

During the 2019 haze episode, the peat forest smoke indicator developed by NERI was used and it established that $PM_{2.5}$ mainly originated from peat-land burning in the region as analysis conducted on it revealed higher fractions of the unique ratios of organic carbon in the carbonaceous profile of $PM_{2.5}$.

This article below, contributed by Associate Professor Yu Liya, the team lead of the five-year research collaboration with NERI, expands on the findings of the recurrent peat forest smoke which have emerged from the $PM_{2.5}$ characterization research project.

Peatland fires causing smoke haze

TRANSPORTED PEAT-FOREST SMOKE IN A DECADE: MAJOR CHARACTERISTICS AND FUTURE CHALLENGES

The state of our urban atmospheric environment can be complex, unpredictable, and yet ever-changing. Being situated along the coastal line in equatorial Asia, complexity and unpredictability reign as a result of constantly changing and free flowing transport of all kinds of anthropogenic and biogenic emissions from domestic sources, as well as influences from the transport of emissions from transboundary land- and ocean-based sources. Weather patterns and conditions play a significant role in the transport of such emissions, and can substantially affect the amounts, composition and duration of airborne components in the ambient air in Singapore.

Monsoon seasons, where predominant winds blow from the north-east (December to February) or the south-west (June to September), tend to carry more transboundary emissions including biomass burning smoke towards our city state. Between 2011 and 2019, transported biomass burning smoke accounted for an average of approximately 30% of urban $PM_{2.5}$ concentrations in Singapore.

Two of the most significant smoke haze episodes experienced in Singapore occurred in 2013 and 2015, each of which had its own distinctive features. The June 2013 episode brought heavy smoke plumes across the Malacca Strait, enveloping the southern Malayan peninsula (see Figure 1). This was due to an anomalous wind direction driven by Typhoon Leepi formed around the Philippines, in combination with westerly/south-westerly winds. This episode highlighted how the weather conditions and events in one part of the region can be closely tied to events in another.

Figure 1. *Satellite Image of Transboundary Smoke Resulting from Peat-Forest Burning in June 2013 [taken from https://earthdata.nasa.gov/labs/worldview/]*

Unlike the two-week incidental smoke event in 2013, the south-west monsoonal smoke in 2015 persisted for around three months, marking the longest smoke episode in Singapore. The south-west monsoon in 2015 coincided with an El Nino year, which brought about extraordinarily drier air and soil surfaces, making the land much more susceptible to fire sparks and rapid spread over large areas once fires occur. This was most vividly demonstrated by persistent plumes springing up underground, underscoring one of the unique features of peat-forest smoke in the Maritime Continent.

Underground burning of peat forests greatly differs from forest fires occurring in temperate and Oceania countries such as Australia. While fires rapidly vanish on-ground materials, underground burning can continue for a much more prolonged duration because of the abundant combustible materials available in the soil, namely, rich organics in peat formed by degraded plants accumulating for tens of thousands of years (Sorensen, 1993). Such underground simmering releases into the atmosphere larger amounts of carbonaceous compounds that are transported to downwind environments including Singapore's. These carbons in $PM_{2.5}$ detected during the 2015 episode were on average approximately 800 years old (Wiggins et al. 2018). This is a piece of evidence that sizzling away the ancient biomass underground aggravates the carbon burden shouldered by our atmosphere.

Transported peat-forest smoke significantly alters the physicochemical properties of ambient fine particulate matter in our ambient environment. Carbonaceous compounds comprising organic carbon (OC) and elemental carbon (EC) are the leading chemical class in smoke laden $PM_{2.5}$. Of this class, attributes relating to the origins of peat-forest smoke can be assessed from the proportion of "char"-like EC and "soot"-like EC in $PM_{2.5}$[1]. A larger amount of char-EC than soot-EC signifies smoldering-prominent burning which tends to emit more organic gases and particulates (Page and Hooijer 2016, Stockwell et al. 2016), a possible indication of more underground burning such as peatland burning. When the relative concentration flips with more abundant soot-EC, flaming (a possible indication of more ground-level burning such as on-ground forest fires) predominates with more emissions of inorganics such as sulfates and heavy metals (Kim et al. 2018).

The profiles between char-EC and soot-EC in $PM_{2.5}$ since 2011 showed that there is an increasing dominance of flaming-prominent smoke, with the strongest extent in 2015 (Lan et al. 2021). The increased extent in flaming coincides with enhanced anthropogenic activities reflected by expanded use of peatland occupying >60% of original pristine peat-swamp forests by 2015 (Miettinen et al. 2016), yielding drier soil surface, and more on-ground combustibles such as for example settlement-built structures. Interestingly,

[1] Elemental carbon (EC) found in smoke laden $PM_{2.5}$ can be categorised into two types – char and soot. Each of these types form under a different set of conditions (for example temperature, oxygen content) and thus have differing characteristics in their relative quantity, useful to assess their origins.

this trend is reversed showing a more smoldering-dominant smoke in 2019 (Lan et al. 2021). Being similarly an El Nino year in 2019, the reversed trend after 2015 could indicate that peatland restoration efforts, which includes re-wetting and re-vegetating peat-lands to replenish moisture content on- and under-ground, may be rendering more smoldering than flaming when fires occur.

In the coming decade, greater uncertainties and an evolving dynamic can be expected from transported airborne pollutants due to global climate change and its effects on local and regional atmospheric environments. Climate change-related alterations in extreme weather patterns and conditions may have an impact on the formation of secondary pollutants, such as ozone. Concerted investigation will need to be carried out to better understand the processes affecting air pollutants throughout their entire atmospheric lifetime, starting from its inception in the atmosphere to its atmospheric evolution, transport and eventual departure. This will provide a more complete picture to facilitate the development of controls and measures that contribute to good air quality.

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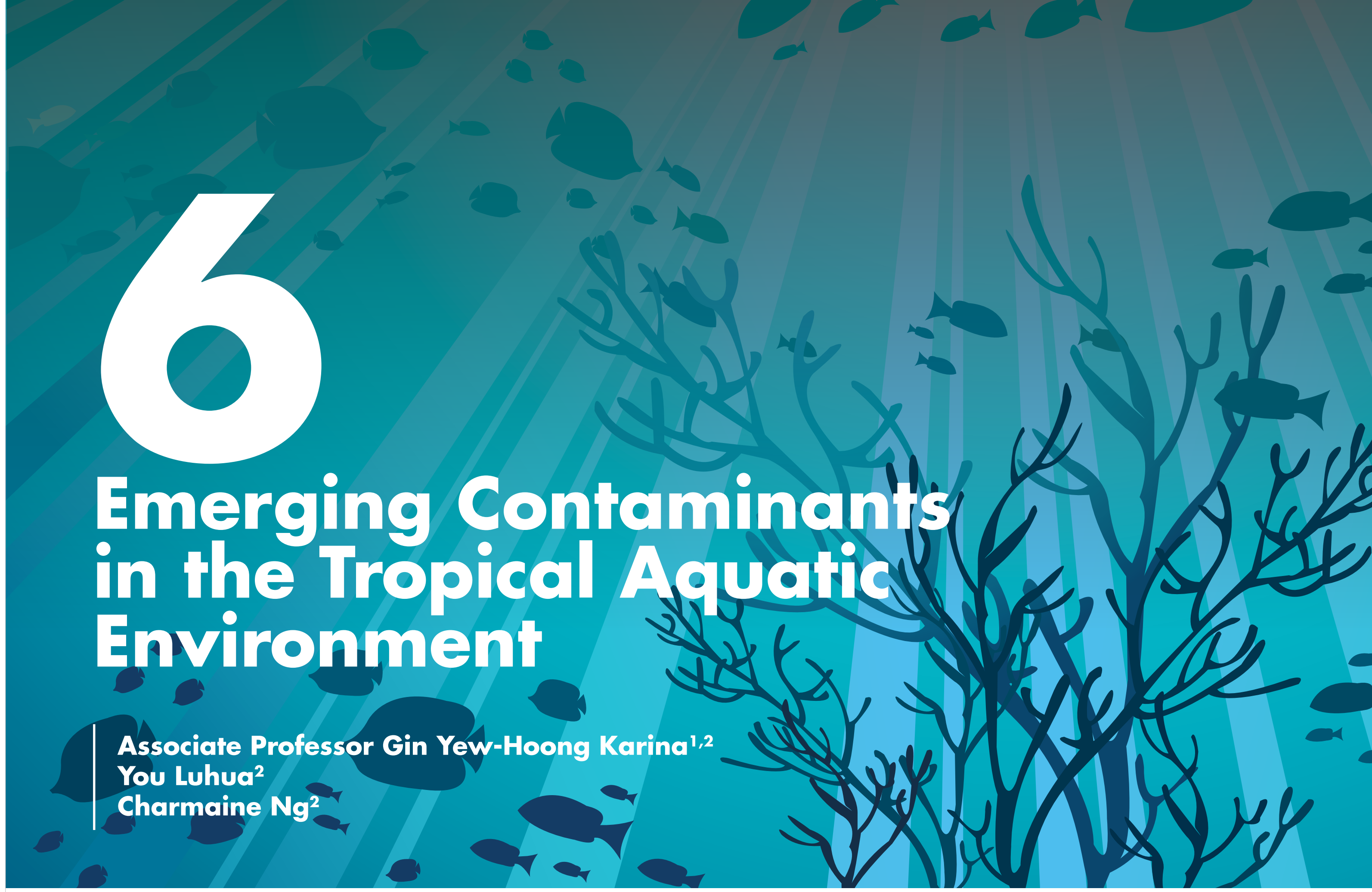

6 Emerging Contaminants in the Tropical Aquatic Environment

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You Luhua[2]
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INTRODUCTION

Emerging contaminants (ECs) are new classes of synthetic or naturally derived water contaminants that have received heightened attention due to their potential or known adverse effects on aquatic ecosystems and human health [1-4]. ECs comprise recently developed industrial compounds. As new industrial products are introduced to global consumer markets, emissions of complex arrays of new EC precursors and by-products may pose an emerging challenge in aquatic environments around the world. Improved detection techniques and toxicity testing methods have allowed prevalent contaminants that have persisted for some time in the environment but were not previously detected or known to have harmful eco-toxicological effects to surface and be better understood [3]. This essay provides an introduction to ECs and the emerging science surrounding it based on research done by NUS and others. These findings should prove helpful to citizens and environmental managers alike in understanding this topic better.

CLASSES OF ECS AND RECOGNISED SOURCES

Representative compound classes include persistent organic pollutants, hormones, endocrine disruptors, human and veterinary pharmaceuticals, personal care products (PPCPs), per- and polyfluoroalkyl substances (PFASs), disinfection by-products, and nanoparticles, as listed by the US

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Environmental Protection Agency [5]. Rising urbanization has led to increased quantities of consumer and health care products that are released into the urban water cycle (UWC). In many overseas countries, ECs enter the UWC mainly via the sewer system and incomplete removal by wastewater treatment plants (WWTP), as well as from overflow and outflows from leaky sewage lines that end up contaminating receiving water bodies and compromising water quality [6]. The occurrence of ECs is a public health issue that is particularly relevant to water scarce countries which rely heavily on the reuse of treated wastewaters for non-potable use. Although sewage is an important contributor to ECs in the environment, other recognized sources include landfills, chemical storage facilities, firefighting training sites, feed lots of animal feeding operations, runoff from industrial sites/fields, recreational activities and atmospheric deposition [7].

GROWING ACADEMIC INTEREST

Over the last two decades, the scientific community has made great strides in building the knowledge base of ECs with a clear rise in global output of EC focused scientific papers. The ubiquity and diversity of ECs have been documented in urban surface waters worldwide with rapid advances in analytical techniques [2, 3, 6]. Low concentrations (ranging between ng/L to µg/L) of ECs have been detected in urban watersheds, although the continuous exposure of aquatic communities to ECs could potentially lead to bioaccumulation and long-term health effects [3, 6].

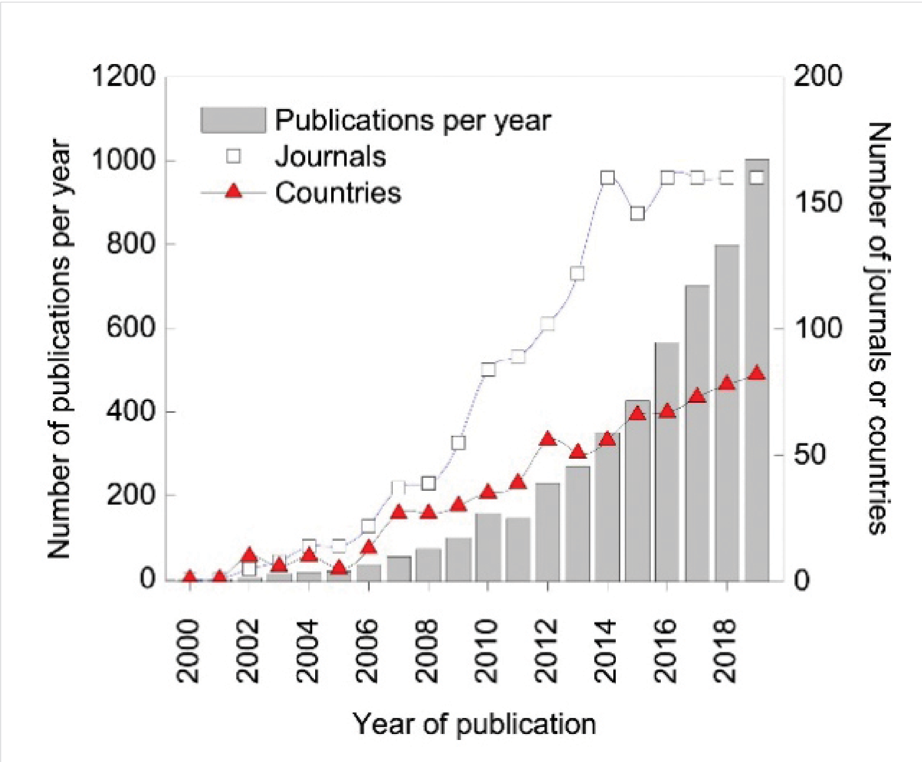

Figure 1. *Evolution of the number of published papers, journals and countries publishing on ECs between 2000 and 2020 [8]*

ANTIMICROBIAL RESISTANCE

One class of ECs that is of growing public interest is antibiotic resistant bacteria. Antibiotics, used for medical treatment of humans and animals, pose a public health concern as persistent exposure to antibiotics could result in antibacterial drug resistance. The World Health Organization has also recognized the occurrence of antibiotic resistant bacteria/genes and that this is one of the most important public health threats. Over the period of 2015 – 2019, our team conducted various studies to understand the levels of antimicrobial resistance in Singapore's water bodies. One study involved the monitoring of antibiotic resistance occurrence patterns in local marine waters, focusing on Extended-spectrum β-lactamases (ESBL) resistant bacteria as these are resistant to the last resort antibiotics. Average concentrations of 10 CFU/100mL of ESBL resistant Escherichia coli at coastal and aquaculture sites were detected, which were relatively higher than those detected in a 2010 coastal study of recreational waters in the Netherlands, where average concentrations were one CFU/100mL [10, 11]. The occurrence of ESBL-producing multidrug resistant E. coli has also been reported in coastal and recreational waters of Brazil, Norway and India [12-14]. In another study, antibiotic resistance genes were used as a proxy for antimicrobial resistance. Concentrations of sul1 genes (encoding resistance to sulphonamides) relative to 16S rRNA bacterial genes were measured in different marine water types [10, 15, 16]. Concentrations ranged between 10-5 – 10-2 which were comparable to waters from aquaculture sites in South Korea (10-6 – 10-5), China (10-3) and Japan (10-3) [10, 16-19]. These concentrations were comparable to ballast water and harbour waters in California (10-7 – 10-2) and South Africa (10-4 – 10-2) with the exception of harbour waters in China (10-1 – 101), which were a magnitude or more higher than those measured in Singapore [16]. These studies offer valuable data on the levels of antimicrobial resistance in Singapore's aquatic environments.

PFAS

Another EC is per- and polyfluoroalkyl substances (PFAS), which are found in packaging, fire-fighting foam, fabrics, upholstery, Teflon materials (non-stick surfaces), and more., and have bioaccumulative effects and are carcinogenic in nature. Studies [20-27] have highlighted that the dominant species of PFAS has changed over the years, from the longer chain, more hydrophobic compounds such as PFOA and PFOS, to short chain, hydrophilic compounds, such as PFBA and PFBS. This result is consistent with industry trends where there is a gradual shift from the more toxic hydrophobic long chain PFASs to shorter chain compounds or PFASs with ether bonds which are perceived to be less bioaccumulative and persistent in the environment [21, 22]. Previous surveys from an urban water body in Singapore indicated total PFASs levels of <14.2-80ng/L [20, 22], relatively lower than the data reported in urban surface waters in Sweden [28] and in Beijing, China [29], and were of same magnitude as the concentrations found in Tokyo Bay of Japan [30] and river estuaries of South Korea [31]. The concentrations detected for PFOS (<24ng/L) and PFOA (<21ng/L) were lower than USEPA's health advisories for drinking water (70ng/L) for both compounds combined [32]. These findings provide an insight into the dominant species of PFAS present in Singapore waters as well as the concentration levels and how they may compare with other countries.

Many of the world's plastic containers and bottles are contaminated with toxic PFAS

DEVELOPMENT OF TOOLBOX OF TARGET ECS AND MODELLING APPROACH

Based on the properties of the various ECs (including several antibiotics, PPCPs, EDCs and artificial sweeteners) measured in a suite of diverse environments, we developed a toolbox of target ECs to act as chemical markers for diffuse sources of pollution in urban surface waters, including the ability to differentiate contaminant sources, such as sewer leakage, illicit discharges or surface runoff. This provides water managers with information to reliably diagnose water quality impacts and follow up accordingly with water protection measures. The chemical markers selected were assessed based on a suite of criteria, including the detection frequency of the chemical; the detection ratio (namely, the ratio between median concentration and method quantification limit of a compound); attenuation rates (namely, biodegradation, sorption and abiotic degradation) in wastewater treatment processes; and the concentration ratio of labile to conservative compounds. Interestingly, chemicals such as the artificial sweeteners like acesulfame, cyclamate and saccharin, turned out to be suitable chemical markers of sewage leakage in surface waters. The data from some of the aforementioned studies has also been used to develop a comprehensive monitoring and modelling approach for describing the fate and transport of ECs in Singapore waters, which can be used for event prediction and real-time forecasting of water quality [58, 59].

CONCLUSIONS AND FUTURE STUDIES NEEDED

This essay highlights some areas of research on ECs and provides valuable data needed for exposure assessments, dose response and risk characterization in risk and environmental impact assessments. These studies contribute to an understanding of the trends and behaviour of ECs in Singapore's waters and may help in establishing appropriate water quality guidelines for the management of our water quality. However, more studies are needed to comprehensively evaluate the classes of ECs present in interlinked aquatic environments, their concentrations, and fate and transport, to develop strategies to manage EC emissions in the UWC and environmental landscape [6]. There is also a need for continued effort in the development of analytical methods and surveillance of EC compounds, as economies progress and new contaminants evolve. Risk based screening models and framework will be essential tools in developing recommendations and water management policies to mitigate the spread of ECs.

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7

Biomass Burning and $PM_{2.5}$ in South-East Asia: Detection, Evolution and Forecasting

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Over the last few decades, transboundary haze has become an annual occurrence in Southeast Asia (SEA) although its severity varies from year to year depending on environmental conditions. Forest fires are a source of haze/smoke generation and is commonly started as a means to clear land for commercial or industrial purposes as well as for basic agricultural usage by small landowners. Smoke ejected into the atmosphere is transported by seasonal winds to the wider SEA region, including Singapore.

Historically, haze events tend to occur between the months of June and early October which coincides with the Southwest Monsoon (the traditional dry season in Brunei, Indonesia, Malaysia, Singapore and southern Thailand). The severity of haze episodes varies from year to year, with particularly intense episodes having occurred in 1997, 2006, 2010, 2013, 2015 and 2019. A few of these episodes were exacerbated by the presence of the El Nino tropical phenomena which increased the seasonal dryness in SEA. As an example, during August-September 2019, Singapore experienced its most recent haze episode which lasted several weeks. During this period, the NEA 1-hour $PM_{2.5}$ concentration peaked at a maximum of 159 µg/m^3 on the 14th September at 3pm local time. Such a rapid air quality deterioration alarmed local authorities and public at large. Episodes like these highlight the need for adopting advanced technologies for haze monitoring and forecasting ranging from in-situ instrumentation, high frequency satellite imagery and advanced modeling techniques. The purpose of this paper is to highlight the status of these technologies from a Singapore-centric perspective. Much of the work described here was done at NUS/CRISP in close collaboration with NEA and the Meteorological Service Singapore (MSS).

HAZE MONITORING: FROM GROUND INSTRUMENTS TO SATELLITES

Ground instruments play a very important role during severe haze episodes and in routine air quality monitoring. During clean and clear days, these sensors provide a baseline of the state of local environment. During severe haze episodes they serve as ground truths as well as a benchmark against which the severity of an episode can be evaluated. In Singapore, NEA hosts a ground network of several $PM_{2.5}$ instruments that provide both direct and indirect measurements of $PM_{2.5}$ concentrations island wide. This network provides near-real time measurements of aerosol particle concentration for both rapid response and policy making from local authorities.

However, much of the smoke particles generated during biomass burning events in the southern ASEAN region are traditionally transported within and above the boundary layer (lower part of the atmosphere) and hence there is a need to monitor not only the extent of the smoke cloud but also its horizontal and vertical distribution to better assess the potential particulates that are transported to ground levels by meteorological conditions.

To do this, NUS hosts several instruments capable of doing a vertical profiling of the atmosphere and can be used for multiple studies [for example 1,2]. One of them is an AERONET[1] Sun-photometer which is capable of measuring the total concentration of aerosol or smoke particles at multiple spectral bands from the ground to the top of the atmosphere (the so-called aerosol optical depth or AOD). AOD is also a standard data product generated by environmental satellites and is typically used as a proxy for particle concentration measured by standard $PM_{2.5}$ samplers at the ground level.

The second instrument is a MPLNET[2] micro-pulse LIDAR instrument capable of doing near real time vertical scanning of the atmosphere by sending a laser beam to the upper layers of the atmosphere and measuring its back-scattered or return signal. Besides detecting cloud height, this instrument can also measure the altitude of the aerosol/haze layers, specially aloft layers that carry long range transported smoke. However, all these useful instruments are limited by its location and numbers; some are very expensive to deploy specially over remote areas and given the vast geography of SEA, it is unrealistic to deploy them in large numbers.

To overcome these ground monitoring difficulties, at CRISP we take advantage of the large spatial coverage that environmental remote sensing satellites can provide over our region. These satellites do carry spectral imaging instrumentation capable of detecting the signature of clouds and aerosols over vast geographical areas. Over the last few years CRISP have been using the capabilities of the Moderate Resolution Imaging Spectroradiometer (MODIS) on board of NASA's Terra and Aqua satellites to detect and monitor forest fire activity and smoke/haze dispersion (Figure. 1).

[1] AErosol RObotic NETwork (https://aeronet.gsfc.nasa.gov/index.html)
[2] Micro-Pulse Lidar Network (https://mplnet.gsfc.nasa.gov)

Satellite technology does not stay static however. Recently we have the availability of high frequency imaging satellites like JAXA[3] Himawari8/9 that is capable of imaging the entire Asian hemisphere every 10 min. The Himawari8/9 satellite series is well equipped for monitoring aerosols and cloud particles at a relatively high spatial resolution (2 Km.). An example of such a capability is shown in Figure. 1.

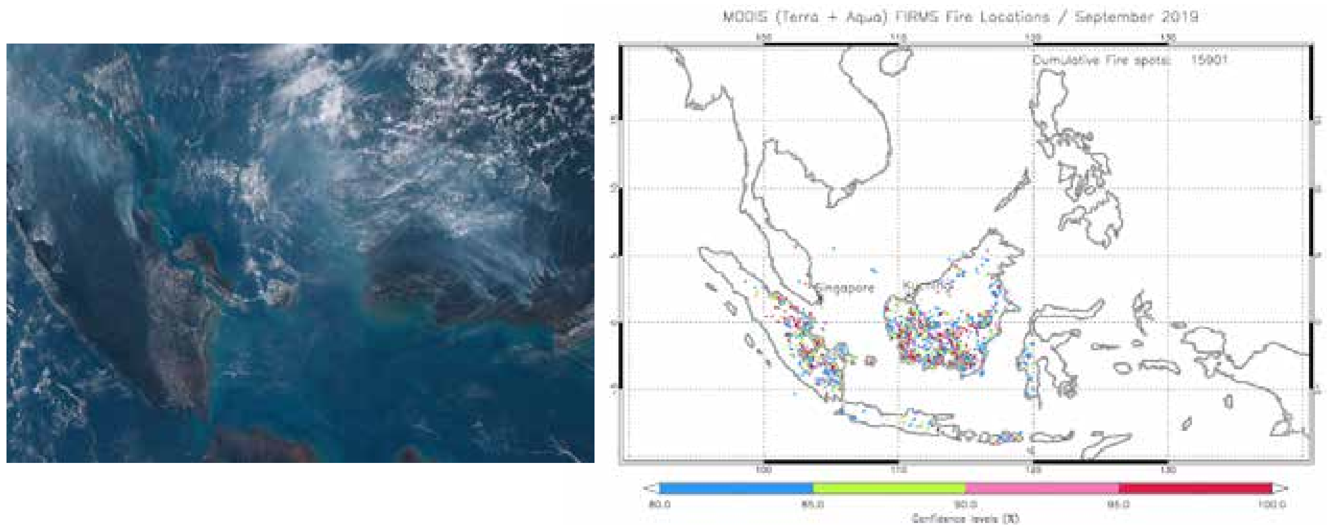

Figure 1. LEFT: *MODIS (Aqua + Terra) thermal anomalies/fire locations corresponding to September 2019 distributed by NASA FIRMS. Singapore and Kuching locations are shown ([3]).* **RIGHT:** *Forest fires detected by Himawari8 over Sumatra and Borneo on 11/09/2019 at 13:00 Hrs. Image courtesy of Japan Meteorological Agency (JIMA) and Center of Environmental Remote Sensing, Chiba University*

More recently in 2019, the Republic of Korea has launched the Geostationary Environmental Monitoring Spectrometer (GEMS) mission onboard the GEO-KOMPSAT 2B satellite to provide atmospheric chemistry measurements in high temporal and spatial resolution over Asia. GEMS performs observations at the UV-visible spectral range and when operational, it can generate estimates of AOD as well the column amounts of atmospheric O_3, NO_2, SO_2 and other tropospheric gases all important for air quality monitoring purposes. As we can see, the high frequency rate in which images are captured by these recent satellites allow us to monitor in near real time not only the evolution of large smoke events such as the September 2019 but enhance our understanding on interactions between atmospheric chemistry and meteorology.

[3] Japan Aerospace eXploration Agency (https://global.jaxa.jp)

HAZE FORECASTING: CLOUD COVER AND IMPLICATIONS FOR FORECASTING

South East Asia is undoubtedly one of the most difficult environments for satellite observations and in-situ measurements in the world. The high degree of cloud cover, in particular the near endemic presence of clouds introduces an important limitation for monitoring and forecasting phenomena such as smoke/haze transport across the region. To overcome these limitations, the usage/development of numerical models able to simulate trans-boundary pollutant transport and dispersion over the region has become abundantly necessary. Recently, CRISP has developed numerical modelling capability by customizing the Weather Research Forecast with Chemistry (WRF) numerical weather prediction model for Singapore conditions. Multiple studies have been carried out to understand the impact of planetary boundary layer schemes, land use, land cover and model horizontal grid resolution [5, 6].

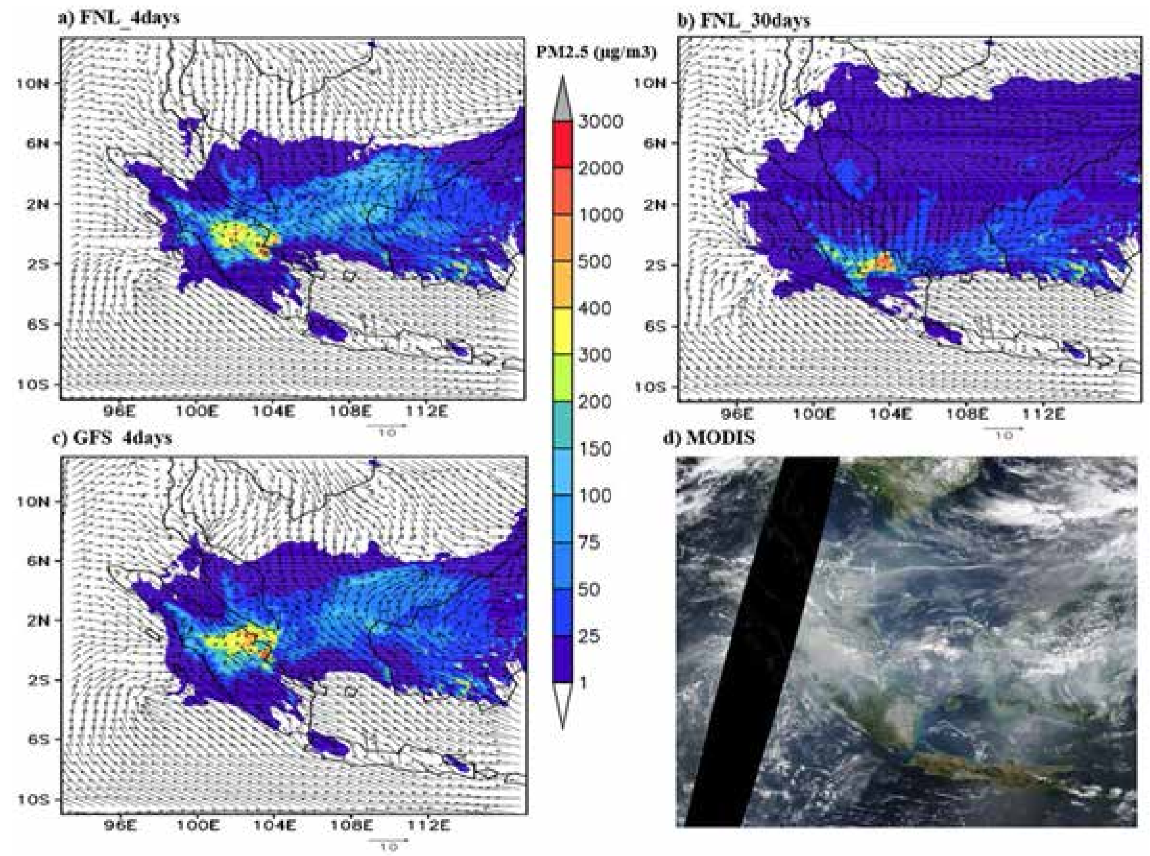

Figure 2. *Comparison of WRF-Chem model simulated $PM_{2.5}$ concentration with surface winds (ms-1) during 03 UTC, 12 September 2019 with available satellite image from Terra MODIS [7]*

A more recent study performed a detailed simulation of the September 2019 smoke episode over SEA (Figure. 2). For this purpose, we used a customized WRF with chemistry model (V3.6) over a 9 x 9 km^2 grid to simulate the formation and transport of biomass-burning smoke across the region. Global Forecasting System (GFS) data is used for meteorological fields while The Naval Research Laboratory's Fire Locating and Modeling of Burning Emissions (FLAMBE) was used as an emissions inventory. For further details see [7].

However, having numerical modelling capability and being able to simulate past smoke events as case studies is the starting point to a more difficult task: Forecasting. Developing an operational forecast modeling platform based on WRF-Chem, for example, is dependent on the availability of various sources ranging from global forecast meteorology, updated regional and local anthropogenic and biogenic emissions, forest fires detection and smoke source generation among others, all of which need to be available in near real time. Finally, having a fully operational forecast model for smoke transport is crucial for early warning purposes. MSS has operationalised a haze forecasting system based on the NAME[4] model, which provides guidance for regional haze assessments [8, 9]. Real-time model forecasts of smoke AOD and surface concentrations of PM_{10} and $PM_{2.5}$ from various modelling centres are available at https://www.mss-int.sg/vfsp-was/forecasts/smoke-forecasts, contributing to a multi-model ensemble developed by the WMO VFSP-WAS[5] SEA regional centre [10]. CRISP and MSS will continuously work together to improve existing modelling capabilities.

OUTLOOK

We hope that in this short manuscript we have described, succinctly, the multiple and advanced capabilities that we have in our hands for understanding, monitoring and forecasting of severe smoke episodes in our region. The new generation of geocentric remote sensing satellites such as Himawari8/9 and GEMS are a real game changer from an environmental remote sensing perspective. The high temporal frequency of data availability coupled with their respective spectral resolution windows provide a solid platform for near-real time smoke/haze monitoring.

If we add the ever-evolving numerical modeling capabilities developed not only by CRISP but by other groups, it gives a good outlook for tackling the difficult task of haze transport forecasting. Finally, a word of caution needs to be introduced here. Our global atmosphere is in constant dynamic change and many atmospheric processes would be disrupted due to global climate change. How will that effect the local and regional atmospheric environment? It is a big unknown and its likely to add further uncertainty to our measurements and models. Before we close, we would like to highlight the support of institutions such as NUS/NEA/MSS for their constant support over the years, without it much of the work described here would not be possible.

[4] Numerical Atmospheric-dispersion Modelling Environment (https://www.metoffice.gov.uk/research/approach/modelling-systems/dispersion-model)

[5] World Meteorological Organization Vegetation Fire and Smoke Pollution Warning Advisory and Assessment System (https://community.wmo.int/activity-areas/gaw/science/modelling-applications/vfsp-was)

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8 Sustaining our Clean Air and Water

> **FUN FACT**
>
> "All new cars procured by the Government will be cleaner energy models from 2023. By 2035, all government cars will run on cleaner energy"

NEA adopts a multi-pronged strategy in pollution management. This includes upstream controls through setting siting requirements and pollution control measures at the planning stage, monitoring regulatory compliance through surveillance and inspection of industrial premises, as well as monitoring of the quality of ambient air, and inland and coastal waters.

MANAGING AIR EMISSIONS

Over the years, regulations and policies have been introduced to reduce air emissions from key pollution sources such as industries, vehicles, and shipping. While our ambient air quality has been progressively improving, Singapore is still working towards meeting the WHO final Air Quality Guidelines (2005) for several pollutants, such as $PM_{2.5}$, PM_{10}, SO_2, and ozone. Being a small, compact and dense city state, where residential, recreational, commercial and industrial activities are within close proximity, striking a balance between continued economic development and clean air to safeguard public health is a constant challenge.

NEA and the relevant government agencies continue to work towards reducing Singapore's domestic emissions of air pollutants. Some of these efforts are outlined below.

LAND TRANSPORT EMISSIONS

Key thrusts of the strategy to further reduce transport emissions include encouraging the use of public transport, cycling and walking over private vehicles, and greening the public and private vehicle fleet.

The public transport and cycling infrastructure will be expanded to support and encourage shifts away from private vehicles. As part of the SG Green Plan 2030, the rail network will be expanded from around 230km in 2021 to 360km by the early 2030s, and the cycling network will be expanded from 460km in 2020 to 1,320km by 2030[1].

To promote a cleaner passenger vehicle fleet, a tax rebate on the purchase of a new electric car or taxi, known as the Electric Vehicle Early Adoption Incentive (EEAI)[2], was introduced from 1 January 2021. The Vehicle Emissions Scheme (VES) was enhanced with increased rebates from January 2021 and higher surcharges from 1 Jul 2021[3]. To green the commercial vehicle fleet, the Commercial Vehicle Emissions Scheme (CVES)[4], similar to the VES, was introduced on 1 April 2021 for light commercial vehicles, while the Early Turnover Scheme for Commercial Vehicles was enhanced on 1 April 2021 with expanded coverage.

For motorcycles, an incentive was introduced in Apr 2018 for early deregistration of motorcycles registered before 1 July 2003. In addition, these motorcycles will be subjected to tighter in-use emissions standards from 6 April 2023[5], and will not be allowed on roads after 30 June 2028.

In support of phasing out internal combustion engines vehicles by 2040 in favour of those that run on cleaner energy, there will be no new registrations of diesel cars and taxis from 2025[6], and all new registrations of cars and taxis must be of cleaner energy models[7] from 2030.

INDUSTRIAL EMISSIONS

Major emitters such as the oil refineries, waste incineration plants and toxic industrial waste

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1 www.greenplan.gov.sg
2 www.mof.gov.sg/docs/librariesprovider3/budget2020/statements/fy2020_budget_statement.pdf
3 https://www.nea.gov.sg/media/news/news/index/increased-rebates-for-cleaner-vehicles-under-enhanced-vehicular-emissions-scheme
4 https://www.nea.gov.sg/media/news/news/index/promoting-the-adoption-of-cleaner-commercial-vehicles
5 https://www.nea.gov.sg/media/news/news/index/in-use-emission-standards-for-older-motorcycles-and-noise-standards-for-all-vehicles-will-be-tightened-in-april-2023
6 www.greenplan.gov.sg
7 www.greenplan.gov.sg

incineration plants are required to have in place in-stack emission monitoring systems to monitor their emissions. NEA will explore enhancement of the emissions monitoring framework and review the industrial air emission limits.

SHIPPING EMISSIONS

The International Maritime Organisation (IMO) adopted the Initial IMO Strategy on reduction of GHG emissions from ships (Initial IMO Strategy) in 2018, with the goal of reducing greenhouse gas (GHG) emissions from international shipping by at least 50% by 2050 compared to 2008, while pursuing efforts to phase them out. Singapore plays an active role at the IMO in the formulation of strategies and measures to reduce such emissions.

In addition, the Maritime and Port Authority of Singapore (MPA) is developing the Maritime Singapore Decarbonisation Blueprint 2050[8] in partnership with industry stakeholders. Some initiatives include the electrification of port equipment, as well as transitioning domestic harbour craft and Singapore-flagged ships away from diesel or bunker fuel towards low-carbon or zero-carbon energy sources. These efforts by the IMO and MPA to decarbonise the shipping industry will also reduce air pollution.

WATER QUALITY

Apart from these efforts which target Singapore's ambient air quality, NEA also regularly monitors the water quality of its inland water bodies, recreational beaches and coastal waters. Since the end of 2020, NEA has been providing Beach Short-term Water Quality Information (BSWI), which is a weekly assessment of water quality at Singapore's seven popular recreational beaches. The assessment is accompanied with advisories and recommended precautions. This equips beachgoers with more current water quality information, which they can use to guide their activities. NEA is also tracking emerging issues of international concern such as marine microplastics and marine litter.

CONCLUSION

A clean environment is a cornerstone of Singapore's sustainable development. NEA continues to monitor key environmental indicators, and refine our measures for effective pollution management to safeguard public health. As new pollutants of international concern emerge, NEA will evaluate these concerns in Singapore's context.

[8] www.mpa.gov.sg/web/portal/home/maritime-singapore/green-efforts/decarbonisation

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