Hong Kong Special Administrative Region
Environmental Protection Department

$PM_{2.5}$ Study for Air Quality Improvement in the Pearl River Delta Region - Feasibility Study

Agreement No. CE 28/2014 (EP)

Summary Report

December 2018

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1 INTRODUCTION

1.1 Background

1.1.1 Studies have shown that particulate matter (PM) pollution, especially those associated with fine suspended particulates ($PM_{2.5}$), is a major cause of adverse health impact and visibility degradation. However, a large part of the PM problem is non-local, implying that a regional approach is needed to quantify the sources so that more effective and targeted control strategies can be formulated.

1.1.2 This Study is the first time in which the environment authorities of Hong Kong, Guangdong and Macao conducted complementary and coordinated research together to allow a holistic understanding of the regional $PM_{2.5}$ problem in the Pearl River Delta (PRD) region (which is also called Guangdong-Hong Kong-Macao Greater Bay Area). Air pollution is a complex problem that respects no boundaries. Comprehensive understanding of this regional problem cannot be achieved without combined effort of scientists from different disciplines, as well as concerted efforts of the three governments.

1.1.3 On November 6, 2014, the Environmental Protection Department commissioned Hong Kong University of Science and Technology R and D Corporation Limited to conduct the “$PM_{2.5}$ Study for Air Quality Improvement in the Pearl River Delta Region - Feasibility Study” [Agreement No: CE 28/2014 (EP)].

1.1.4 In the longer term, successful completion of this Study helps demonstrate how coordinated research with clear objectives set by regional governments can help environmental policy-making, which can serve as a good example for other city clusters beyond the PRD region.

2 OBJECTIVES AND SCOPE OF THE STUDY

2.1 Objectives

2.1.1 The objectives of this Study are:

- To obtain spatial and temporal distributions, and comprehensive chemical compositional data of $PM_{2.5}$ pollutants in the PRD region;
- To map the baseline of $PM_{2.5}$, its precursors and their major constituents in the PRD region in different seasons of the year;
- To identify and quantify the major $PM_{2.5}$ sources, including relative contributions of primary sources (direct emission) and secondary formation (formed in the atmosphere, not directly emitted), major organic aerosol sources and major volatile organic compounds (VOC) precursors for secondary organic PM;
- To develop a fine resolution $PM_{2.5}$ emission inventory for the PRD region;
- To refine the numerical air quality modelling system for $PM_{2.5}$ simulation for investigating emission sources and pollution characteristics, forecasting pollution trends and episodic events, and conducting scenario analysis for potential emission control measures performance evaluations;
- To develop $PM_{2.5}$ conceptual models to identify the major characteristics of $PM_{2.5}$ pollution at different areas in the PRD region;
- To recommend effective and appropriate pollution control strategies;
- To identify the potential biases for the present and future $PM_{2.5}$ monitoring technologies in the PRD region;
- To evaluate the current $PM_{2.5}$ monitoring for compliance and research purposes, and provide recommendations for improving the $PM_{2.5}$ monitoring system as well as individual monitoring station;
- To project the possible changes in composition trend of $PM_{2.5}$ (e.g. sulfate and nitrate) with reference to industrial and economic development in the PRD region for formulating proper air quality management system in the future; and
- To develop a virtual integrated platform to store and visualize all the data and findings obtained in this Study in order to connect and facilitate communications, discussions and co-investigations among relevant academics and experts, and government officials on the air pollution problems in the PRD region.

2.2 Study Area

2.2.1 The Study Area covered the entire PRD region, including Hong Kong Special Administrative Region, Macao Special Administrative Region and the PRD region of Guangdong Province (including Guangzhou, Shenzhen, Dongguan, Foshan, Zhongshan, Zhuhai, Jiangmen, Zhaoqing and Huizhou).

3 MAJOR FINDINGS

3.1 Field Sampling and Chemical Analysis

3.1.1 In Hong Kong, across all the general (not at roadside) sampling sites, sulfate (SO_4^{2-}), organic matter (OM), and ammonium (NH_4^+) were the most abundant components of $PM_{2.5}$. On the other hand, OM, element carbon (EC), and SO_4^{2-} were most abundant at the roadside.

3.1.2 The difference of SO_4^{2-} and NH_4^+ level among locations was insignificant for samples collected in Hong Kong, suggesting that these two species were largely from other regions. The EC levels showed a quite clear gradient of roadside > urban > new town > suburban, consistent with the general environmental characteristics of these sites. The higher OM and EC concentrations at the roadside site suggested that vehicular exhaust would be a major source for the carbonaceous particles there.

3.2 Satellite Remote Sensing and LIDAR Observation

3.2.1 The 15-year (2000 to 2014) average of satellite-retrieved $PM_{2.5}$ concentrations in Hong Kong showed that higher $PM_{2.5}$ concentrations were observed in the central urban areas with very tall buildings and heavy traffic, and in the northwest which is adjacent to Guangdong and thus most susceptible to pollutants transported from Guangdong.

3.2.2 The trend of the annual averaged satellite-retrieved $PM_{2.5}$ concentrations in the PRD region from 2001 to 2015 showed that $PM_{2.5}$ concentration generally increased during the first half of the period and reached the maximum of 44.1 ± 16.8 $\mu g/m^3$ in 2007[1]. An overall decrease in $PM_{2.5}$ concentration after 2008 was observed, as well as a substantial decline in $PM_{2.5}$ from 2014 to 2015. $PM_{2.5}$ concentration reached the minimum of 29.8 ± 11.4 $\mu g/m^3$ in 2015. The level was lower than the World Health Organisation (WHO) Interim Target 1 (IT-1), but still significantly higher than the WHO Interim Target 2 (IT-2), Interim Target 3 (IT-3), and Air Quality Guidelines (AQG), suggesting room for air quality improvement in the region.

3.2.3 For each city in the PRD region, the average satellite-retrieved $PM_{2.5}$ concentration generally had long-term trend similar to that of the PRD region as a whole with cities at the center of the PRD region having much higher $PM_{2.5}$ concentrations. Although decline in $PM_{2.5}$ concentration was generally observed from 2014 to 2015, $PM_{2.5}$ concentrations still exceeded the WHO IT-2 and far exceeded the WHO IT-3 and AQG in all cities.

3.3 Emission Inventory Refinement

3.3.1 A highly resolved 2012 regional emission inventory for the PRD region of Guangdong Province was developed using a bottom-up approach with the best available localized source-based emission factors and emission activity data. A strict quality assurance/quality control (QA/QC) procedure was in place for data collection and calculation. Uncertainty analyses were conducted for emission

[1] The plus or minus values indicated the range of annual average concentrations in the PRD region.

factors and emission estimates to ascertain the inventory data quality. The inventory covered emissions from major sources: power plants, industrial sources, mobile sources, dust sources, VOC-related domestic sources, biomass burning, transport sources and fuel storage, agricultural and husbandry sources, natural sources and others. The inventory accounted for emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_X), carbon monoxide (CO), respirable suspended particulates (PM_{10}), $PM_{2.5}$, black carbon (BC), organic carbon (OC), VOC and ammonia (NH_3).

3.3.2 For 2012, power plant and industry combustion were the major sources of SO_2 and responsible for 27.3% and 49.4% of total emission respectively. On-road mobile was the largest contributor of NO_X, CO and BC, producing 34.4%, 45.4% and 41.4% of the total respectively. The largest PM_{10} contribution was dust, accounting for 47.1% of the total. The major $PM_{2.5}$ emission sources were power plant, dust and industry combustion, accounting for 18.4%, 17.4% and 15.1% of total respectively. Solvent use and on-road mobile were the important VOC sources, accounting for 42.4% and 33.8% of the total respectively. Agriculture and husbandry sources were the largest contributors of NH_3, producing 78.3% of the total.

3.3.3 Compared with the 2010 emission inventory, significant decreases in PM_{10}, $PM_{2.5}$ and NH_3 emissions were observed in 2012. The decreases of SO_2 and NO_X emissions were moderate. The decreasing trend in these emissions could be attributed to the control measures that were implemented between these years. The VOC emission decrease was marginal which was probably because VOC sources were numerous, scattered and thus not easy to control.

3.3.4 The air pollution emissions were allocated to the PRD region of Guangdong Province, which was divided into a 3 km x 3 km grid to explore their spatial characteristics. High SO_2 emissions were mainly in Guangzhou, Dongguan and Foshan which had large combustion point sources such as power plants and industrial premises. NO_X emissions were mainly in the central and southern parts of the PRD region of Guangdong Province with high energy consumption, developed industries, dense population and road networks. CO emissions generally coincided with the locations of industrial premises and road network. $PM_{2.5}$ emissions shared some similarities with PM_{10} emissions which were mainly allocated to the central and southern parts of the PRD region of Guangdong Province. Anthropogenic VOC emissions were mainly in Foshan, Guangzhou, Dongguan, Shenzhen and Zhongshan - the centers of light industries with large consumptions of VOC-containing solvents. NH_3 emissions were mainly in the countryside where livestock and husbandry sources, and agriculture fertilizing were located. BC and OC emissions similarly followed patterns of road network.

3.3.5 Different emission sources displayed distinct monthly, weekly/daily or hourly variations. For example, the monthly characteristics of power plant emission in different cities varied, which were mainly attributed to the differences in their industrial structures, number of industrial premises and their capacities and populations. Emissions of small automobiles like private cars were generally lower during weekdays and started to increase since Friday and peaked on

Saturday, reflecting the local lifestyle. Emissions of large automobiles like trucks were high during weekdays but dropped significantly during weekends.

3.4 Receptor Modelling and Source Apportionment

3.4.1 Positive Matrix Factorization (PMF) Model was employed to identify major $PM_{2.5}$ pollution sources in the PRD region and quantify their impacts. The nine source factors identified for the PRD region of Guangdong Province were vehicle exhaust, residual oil, sea salt, crustal soil, secondary sulfate, secondary nitrate, trace metals, biomass burning and industry. Eight factors were identified for Hong Kong and Macao. Seven of them were also found among the nine factors for the PRD region of Guangdong Province. The eighth factor was a mixture of the industry and secondary nitrate factors. Including non-polar organic compound speciation data from Hong Kong and Macao in the analysis, the model managed to identify contribution from coal combustion. This highlighted the importance of the non-polar organic compounds speciation data in helping to identify sources that would otherwise be unrecognized.

3.4.2 In terms of the source contribution, secondary sulfate was the most significant factor in the PRD region, accounting for 24.1% of total $PM_{2.5}$ mass in the PRD region of Guangdong Province and Macao, and 27.4% in Hong Kong. A significant portion of secondary nitrate in the PRD region of Guangdong Province and Macao was produced within the PRD region. Vehicle exhaust percentages were higher in Guangdong and Macao than in Hong Kong. Residual oil contribution percentages were higher in Hong Kong and Macao due to their proximity to marine activities. Higher crustal soil percentage in the PRD region of Guangdong Province might be related to the intensive land development activities. Contribution from industry was negligible at Hong Kong and Macao.

3.4.3 The monthly variation of the nine source factors showed that all factors shared a general pattern of high in winter and low in summer, except that residual oil showed a decreasing trend after August 2015, which might be a result of the new regulation on reducing the sulfur content of the fuels used in ocean going vessels. Secondary nitrate was almost zero from May to September because higher temperature was unfavourable for its formation in the particle phase. Industry showed a peak in March which might be a result of production ramp-up after the Chinese New Year.

3.4.4 The plot of spatial distribution of $PM_{2.5}$ contributions by sources clearly showed that 1) vehicle exhaust showed slightly higher contributions at the PRD region of Guangdong Province; 2) residual oil was higher at Hong Kong and Macao; 3) contributions from sea salt were concentrated around Hong Kong and Nansha ports; 4) secondary sulfate showed the highest concentration at Zhaoqing; 5) secondary nitrate was higher at Zhaoqing and Jiangmen sites; 6) as a suburban and rural area, Jiangmen was also a hotspot for biomass burning.

3.5 Air Quality Modelling

3.5.1 The updated Pollutants in the Atmosphere and their Transport over Hong Kong (PATH) air quality modelling system was used to examine the pollution transport, transformation, and dispersion characteristics and to identify the $PM_{2.5}$ sources in the PRD region. Four nested modelling domains, with the grid resolution of 27 km, 9 km, 3 km and 1 km respectively, were designed both for the meteorological model and the chemistry transport model (CTM). The modelling system used Sparse Matrix Operating Kernel Emissions (SMOKE) model for emission processing, Weather Research and Forecasting (WRF) as the model for meteorology, and Community Multiscale Air Quality (CMAQ), Comprehensive Air Quality Model with Extensions (CAMx) and Nested Air Quality Prediction Modelling System (NAQPMS) as CTMs. Modelling simulation was performed for 2012 and 2015 – the latter being the year in which field sampling was carried out for this Study. Emission inventories discussed above were used for model runs supported by meteorological data from various sources (Hong Kong Observatory and internet). For QA/QC purpose, simulation differences generated from different models were compared to evaluate their advantages, capabilities and compatibilities. The simulation was validated by observation data. Particulate Source Apportionment Technology (PSAT) module in CAMx was applied to track the emission contributions to simulated PM concentrations by source regions (i.e., Guangzhou, Shenzhen, Hong Kong, Macao, the region outside the PRD region but within the simulation domain and the region outside the simulation domain) and categories (i.e., power plant point source, industrial point source, area source, mobile source, marine source and biogenic source) in 2015. Moreover, different model setting and scheme options were conducted to identify the most influential one(s) on the model performance, especially on secondary organic aerosols (SOA), the part least understood in $PM_{2.5}$.

3.5.2 The 2015 WRF simulation produced wind direction/speed/vectors and temperatures that agreed well with observations in Hong Kong and the PRD region of Guangdong Province in 2015.

3.5.3 The CMAQ simulations of 2015 produced $PM_{2.5}$ concentration field that agreed quite well with observations in Hong Kong and the PRD region of Guangdong Province, reproducing the trends of $PM_{2.5}$ well in all the monitoring stations throughout 2015 but under-predicting consistently by about 3.5 $\mu g/m^3$. This was probably due to some unaccounted emissions from local, regional and super-regional sources.

3.5.4 For SOA, though some uncertainties still existed in the results, both the 1-D and 1.5-D Volatility Basis-Set (VBS) SOA Models reproduced the concentration levels and temporal variations fairly well, while the traditional SOA model did not provide any reasonable result.

3.5.5 PSAT analysis showed that the super-regional contribution was the most important source for the ambient $PM_{2.5}$ in Guangzhou, Shenzhen, Hong Kong and Macao in February, October and December, but its importance decreased substantially in July when the local and regional contributions became more important. The local and regional contributions also increased during episode days. Area emission was the most important source category for the four cities. Mobile emission and marine emission contributed a substantial portion of $PM_{2.5}$ in Shenzhen and Hong Kong, respectively. Point source contribution was less important.

3.6 Conceptual Model

3.6.1 The data used in conceptual model development included results from both the said enhanced emission inventories and the air quality modelling. Backward trajectories (tracing where the air stream came from) were generated by Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model and clustered to help distinguish pollution contributions from different spatial scales (local-, regional- and super-regional-scales). Five stations across the PRD region, including three inland stations - Zhaoqing, Conghua and Nansha - and two coastal stations - Tsuen Wan and Taipa Grande - were selected as the starting locations for back trajectory analysis.

3.6.2 The general patterns of the backward trajectories showed that these five stations were in the same air-shed for most of the time and air masses impacting the PRD region were mostly from northeast, east, south and southwest.

3.6.3 Five clusters were identified at each station, labelled as “NE-long”, “NE-close”, “SE”, “SW-close” and “SW-long”. NE-close cluster accounted for over 50% of the trajectories at the inland stations while only over 30% at the coastal stations. In comparison, the percentages of NE-long at the coastal stations were higher than those at the inland stations. Most of the NE-close trajectories were in spring, autumn and winter while the dominant summer cluster was SW-long at all stations.

3.6.4 Combining cluster analysis with PMF source apportionment, the contributions from each PMF factor in each trajectory cluster were estimated. Secondary sulfate, vehicle exhaust and biomass burning were the dominant factors for the two NE clusters. Secondary sulfate, residual oil and vehicle exhaust were the dominant factors for the other clusters.

3.6.5 Local and non-local contributions to $PM_{2.5}$ from each PMF factors at each station were identified and separated by conceptual model. For factors of secondary nitrate and trace metals, local contributions were always lower than non-local counterparts. In contrast, local contributions of sea salt were always bigger than non-local. In general, coastal stations had higher non-local contribution.

3.6.6 The PRD region was in the same air-shed for over half of the time. When it was separated into two air-sheds, one was formed inland and another was formed along the coast. Different air-sheds had quite distinct local and non-local contributions.

3.7 Integrated Analysis and Policy Relevant Suggestions

3.7.1 Integrated analysis was carried out for four typical episodes in four representative months -February (Winter), July (Typhoon), October (Summer/Fall transition) and December in 2015 - to analyze the contributions from weather conditions and for four scenarios to examine the impacts of hypothetical control measures. Policy relevant recommendations were made based on the analysis results.

3.7.2 The most important meteorological condition for pollution episodes was related to the enhanced stability in the PRD region under the influence of a nearby tropical cyclone to the east/southeast/northeast of the PRD region. Air pollutants could rapidly build up in such conditions. Especially during the weak northerly or northwesterly winds, the concentration of pollutants in Hong Kong and the southern coastal cities of the PRD region rapidly increases, resulting in high levels of pollutants up to one week (in summer or autumn).

3.7.3 Besides tropical cyclone, weak wind conditions might also occur during summer and fall over southern China, causing pollutants to accumulate in the PRD region. From time to time, the trapped pollutants might be brought to Hong Kong if the wind turn northwesterly, increasing pollutant concentrations in Hong Kong.

3.7.4 Short term increases in air pollutants in Hong Kong could also be seen in the winter, usually associated with enhanced north/northwesterly flow. This was particularly noticeable when the dominant wind was weak northeasterly combining with lower temperature (more stable boundary layer) and weaker wind on the surface to cause slow but substantial build-up of pollutant in South China inland.

3.7.5 Four scenarios were hypothesized – with reference to those near-term control measures in the 13^{th} 5-Year Plan, changing to cleaner fuel type, etc. – for modelling to evaluate their impact on regional air quality in the PRD region. They were: Base Case (S1), S1 with strengthened control on transportation and power plants (S2), S2 with further strengthened control on area/industrial sources (S3), and S3 with China outside the PRD region implementing similar level of control (S4). The validated WRF/CMAQ model was used to simulate the changes in air quality in the region in the four scenarios.

3.7.6 The modelling results showed that the four hypothesized scenarios would help to reduce $PM_{2.5}$ concentrations throughout the entire PRD region, in particular in the north western part of the PRD region. $PM_{2.5}$ concentrations at all Hong Kong monitoring stations would be reduced by about 2 to 5 μg/m^3.

3.7.7 Based on the above analysis, the following policies were suggested:

- Strengthen regional collaboration on air quality management
- Establish a comprehensive regional atmospheric monitoring network
- Establish a comprehensive dynamic regional air pollutant emissions inventory
- Develop regional forecasting and early warning system for major air pollution episode
- Optimize the spatial layout of industrial areas to help control the area sources and reduce regional secondary pollutants
- Strengthen the prevention and control of mobile source pollution and encourage non-motorized transport
- Tighten the control of major pollution sources and reduce air pollutant emission
- Optimize the energy structure to reduce coal consumption
- Strengthen the control on ammonia emissions and open burning

- Improve the understanding of air pollution processes through joint scientific studies

4 CONCLUSIONS AND RECOMMENDATION

4.1 Conclusions

4.1.1 The remote sensing analyses showed a substantial reduction in ambient $PM_{2.5}$ in the PRD region since 2008; particularly impressive reduction was observed since 2012. However, the average annual $PM_{2.5}$ concentrations over the cities of the PRD region were still high when compared with the corresponding WHO recommended AQG, implying that further work needs to be done to protect public health against air pollution in the PRD region.

4.1.2 The PMF source apportionment results for the PRD region in 2015 was very stable and reliable. Nine source factors were identified for the PRD region of Guangdong Province while eight factors for Hong Kong and Macao, in which seven were common factors and the two remaining factors (industry and secondary nitrate) of the PRD region of Guangdong Province were mixed to form the eighth factor for Hong Kong and Macao. The PMF method could further identify the contribution from coal combustion after non-polar organic compound speciation data from Hong Kong and Macao were added to the data being analyzed. This highlighted the importance of non-polar organic compounds speciation data in helping to identify sources that would otherwise be unrecognized.

4.1.3 Secondary sulfate and vehicle exhaust were the top two sources of $PM_{2.5}$ in the PRD region of Guangdong Province, Hong Kong and Macao. Secondary nitrate was the third largest contributor in the PRD region of Guangdong Province and Macao while residual oil was the third in Hong Kong. Crustal soil, biomass burning and industry showed the highest contribution in the PRD region of Guangdong Province, residual oil was the highest in Macao, while sea salt posed similar impacts on the three regions.

4.1.4 Local and non-local contributions to $PM_{2.5}$ in the PRD region were identified and separated by conceptual model. Local contribution was usually lower than non-local counterpart. In addition, local contribution was higher inland than near the coast, and was higher in summer than in winter.

4.1.5 The PRD region was in the same air-shed for over half of the time. When it was separated into two air-sheds in the other period, inland area tended to form a separate air-shed during spring and summer while coastal area did in autumn and winter.

4.1.6 The $PM_{2.5}$ level in the PRD region is largely driven by meteorological conditions. But during some unfavourable meteorological conditions, stringent local emission control can be used to alleviate pollution levels.

4.1.7 As more stringent control policies were being implemented in the PRD region over the years, their air pollutant emissions decreased from 2012 to 2015. Greater extent of reduction is expected in the near future. For example in 2020, if the near-term control measures in the 13th 5-Year Plan for the PRD region of Guangdong Province and China and the Air Pollution Control Strategy for Hong

Kong are implemented, emission in all source categories, except marine emission, can be reduced.

4.2 Recommendations

4.2.1 Every policy suggestion should be supported and illustrated by as much data as possible, particularly the aforesaid 10 suggested policies which emphasized more efforts and more cross-regional collaboration from science to policy in the PRD region.