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Mapping of Airborne Particulates in Phnom Penh, Cambodia: Comparisons with Bangkok, Thailand and Phoenix, Arizona

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Abstract: The city of Phnom Penh is experiencing growth and, with this growth, an increased level of air pollution in the form of airborne particles that are attributed to increased vehicle traffic in the city – vehicular exhaust and re-entrained dust. For this study, airborne particulates were counted and sorted using a six-channel laser particle counter. Initial sample counts were taken at 88 sites within the city of Phnom Penh, Cambodia, on days representative of dry season conditions. A subset of 33 sites was re-sampled on a day representative of the wet season. Objectives of this study are to provide a baseline count for airborne particulates in the city of Phnom Penh, and to explore the characteristics of the particulate counts utilizing summary statistics and maps. The median Phnom Penh city-wide fine and coarse particle counts are $1.07 * 10^8 /m^3$ and $1.36 * 10^6/m^3$, respectively. While the fine particle count can be attributed to vehicle exhaust, the coarse particle count is attributed to re-entrained road dust and dirt roads. The overall coarse particle count is influenced by a number of hot spots across the city. Selective paving of these hot spots will greatly reduce the level of airborne coarse particulates.

Key words: Phnom Penh, Cambodia, particulates, particle counter, air pollution.

Introduction

The city of Phnom Penh, Cambodia (11° 33′ N 104° 55′ E) has experienced rapid growth which in turn has created an increased awareness of air pollution. Fenger (1999) links air quality in cities to level of development and income, initially increasing with a growing income up to a point. Grossman and Krueger (1995) have estimated that point to occur at a per capita income of 8,000 USD. Given Phnom Penh's average per capita income of 1,550 USD, as measured at purchasing power parity (Worldbank, 2008), the city will likely experience an increase in air pollution as the city grows and the country develops. Sources of air pollution in Phnom Penh include factories that utilize old technologies devoid of air pollution controls, private power generators used to augment an unreliable power grid, and the burning of biomass fuels (United Nations, 2005). Excessive particulates are evidenced by dust masks worn by many motorists and the presence of individuals hired to sweep the streets. Many of the airborne particles are attributed to increased vehicle traffic in the city – vehicular exhaust and re-entrained dust (United Nations, 2005; Kashima et al., 2001; Furuuchi et al., 2006). The vehicle exhaust is primarily attributed to the growing number of "motodops" (small motorcycles) that account for the majority of transportation vehicles in the city – an estimated 700,000 motorcycles versus 130,000 cars (DoE News, 2007). Motorbikes account for a disproportionate amount of emissions (relative to fuel consumption) due to their two-stroke engines, further exasperated by the prevalence of imported second-hand vehicles that

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produce more pollution than new vehicles. Dust is generated by winds blowing in from the countryside as well as unpaved shoulders lining paved roads (coating paved roads), material spillage onto roads, the storage of construction materials on roads, and the large number of unpaved roads in Phnom Penh (United Nations, 2005). It is estimated that 30% of Phnom Penh's 4,800 km of roads are unpaved (DoE News, 2007).

Kashima et al. (2001) monitored NO_2, CO, SO_2 and particulate matter in Phnom Penh from 2 to 7 days (dependent on pollutant). While the other pollutants were considered low, below World Health Organization (WHO) guidelines, particulate matter concentrations (PM-10 and TSP) were high and seen as a major health concern. A limited sampling of TSP (three sites) was also conducted by Furuuchi et al. (2005), where PAH concentrations were found to be high compared to other Asian cities. These high concentrations were attributed to diesel generators and the burning of biomass fuels.

Airborne particulates exist in the atmosphere with a bi-modal distribution of fine and coarse particles. Fine particles of less than 2.5 μm are associated with high temperature emission sources (e.g. vehicular exhaust), while coarse particles of greater than 2.5 μm are associated with soil or road dust re-entrainment (Sweet et al., 1993). The fine particles are capable of penetrating deep into the lungs, while coarse particles (2.5 to 10 μm) reach the nose and throat. Numerous epidemiological studies have shown positive correlations between fine airborne particles and respiratory and cardiovascular mortality (Pope et al., 1995b; Vedal, 1997; Zanobetti et al., 2000). Brunekreef and Forsberg (2005) provide evidence that increased coarse particle concentrations are linked to increased pulmonary disease, asthma, and respiratory-related hospital admissions. A review of epidemiological studies by Dockery et al. (1993), and Pope et al. (1995a) attribute respiratory disease to airborne particle concentrations common to many U.S. cities. Ostro et al. (1999) and Mar et al. (2000) found an association between air pollution and mortality in the cities of Bangkok, Thailand, and Phoenix, Arizona, respectively.

The city of Phoenix, Arizona is located at 33° 32′ N 112° 4′ W in the heart of the Sonora desert. The city was once considered a healthy destination for people with respiratory ailments, but the cities location within a desert valley and rapid growth has resulted in high pollution levels. Inversions across the valley often trap pollutants in the city forming a brown cloud of haze.

The city of Bangkok, Thailand is located at 13° 45′ N 100° 31′ E. The city is often shrouded in smog, generally associated with vehicle exhaust. The high pollution levels are especially notable at street level where a number of residents wear surgical masks. However, over the past decade the city has worked to reduce the pollution by cracking down on polluting vehicles, promoting the use of natural gas, developing rail alternatives, and tightening air quality standards.

Objectives of this study are to provide a city-wide count of airborne particulate pollution in the city of Phnom Penh, to explore the characteristics of the particulate counts, and to provide a spatial rationale for the management of the city's air pollution, including the possible location and number of permanent monitoring sites. In addition, a case is made for use of a laser particle counter to determine relative levels of airborne particulate pollution in a developing country – an instrument that is simple to use, requires only battery power, and has no analytical costs.

Methodology

A laser particle counter was used to count ambient airborne particles. The particle counter allows for a shorter sampling period (one minute) in lieu of gravitational measurements which traditionally require 12 to 24 hours. Furthermore, the use of virtual impactors (used to separate particle sizes for gravimetric analysis) may cause the breakup of particles in an aggregate form, giving spurious fine particle loadings (William and Vermette, 1991). Tippayawong et al. (2006) noted that the counting of particles is a significant alternative or supplement to gravimetric analysis (mass loadings).

Airborne particulates were counted and sorted using a six-channel (0.3, 0.5, 0.7, 1.0, 2.0, and 5.0 μm) laser particle counter (Met One, Model 237). The particle counter uses a laser diode light source and collection optics for particle detection. Incoming particles scatter light from the laser diode beam in the direction of the collection optics. The collection optics focuses the light on a photo diode that converts the bursts of light into electrical pulses. The pulse height is proportional to the particle size. Both the pulse and intensity are measured to determine the count and size, respectively. The laser particle counter was calibrated by the manufacturer (Met One) three weeks prior to the initial sampling.

Initial sample counts were taken at 88 sites within the city of Phnom Penh, Cambodia from January 15 to17, 2007. These dates are representative of dry season conditions in Phnom Penh. A subset of 33 sites was re-sampled on June 19, 2007, a date representative of the wet season in Phnom Penh (the city had received rainfall on several days before the sampling). Travel between counting sites was by motorized tuktuk. Sites were chosen at approximately one-kilometre increments along major urban roadways and all sampling occurred between 8:00 a.m. and 4:00 p.m. A subset of sites included a transect from the Central Market to the water front (see area A in Figure 1), a two-block area within the city (see area B in Figure 1), and the city dump which was sampled during the wet season (see area C in Figure 1). Particle counts were also made at a few sites in the Cambodian countryside. Sampling sites were marked with a hand-held Global Positioning unit (Garmin, E-trex), and recorded as UTM coordinates using a WGS84 datum.

Counts at each site were taken a few metres from the tuktuk (motor turned off) and every attempt was made to avoid immediate sources of particulates (e.g. cooking, machinery, and idling vehicles). Counts were taken at one-minute increments with a flow rate of 2.83 L/min

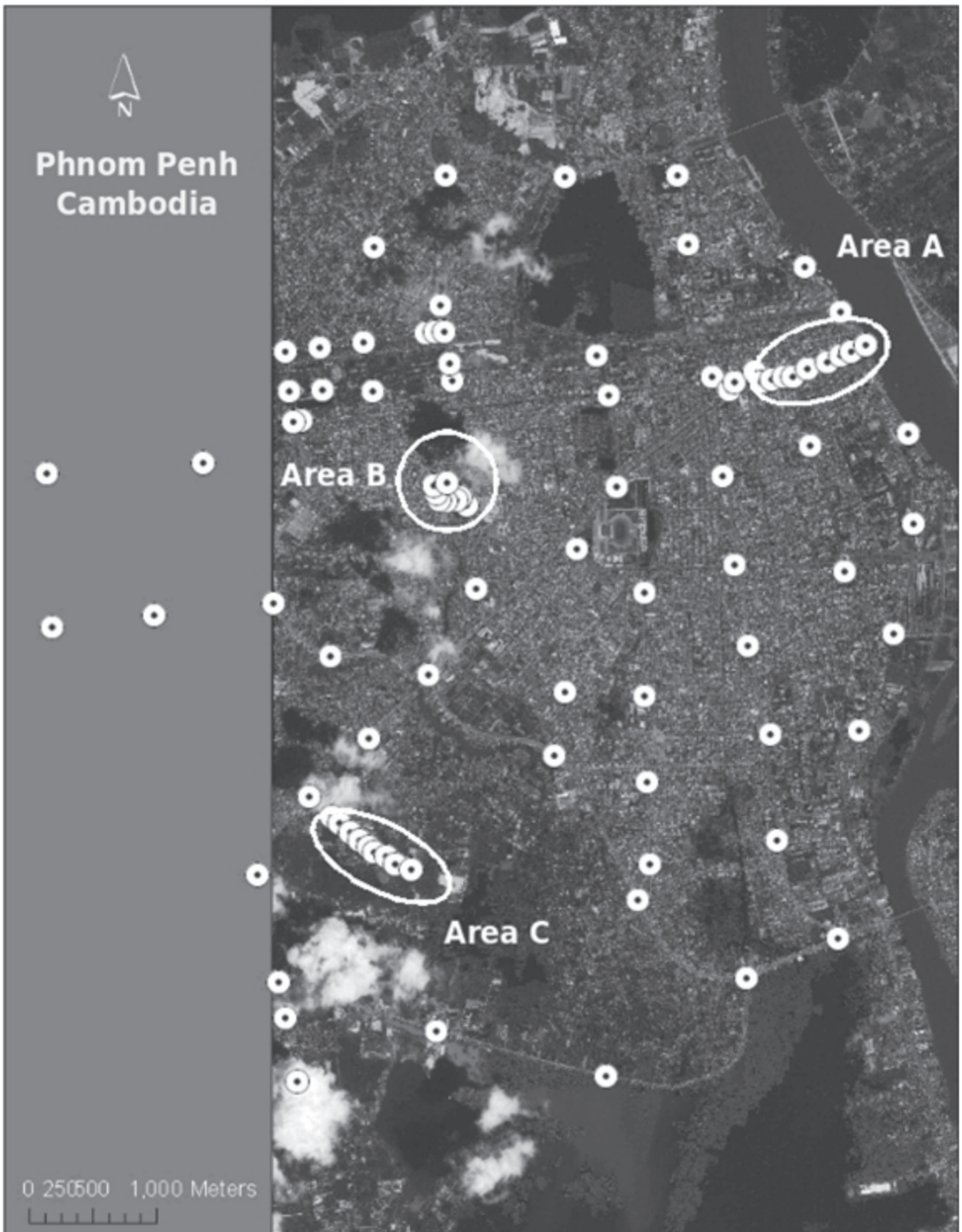

Figure 1: Phnom Penh sampling sites.

(0.00283 m^3/min). Values are presented as a count per cubic metre (count/m^3).

For the purpose of this study, fine particulates are defined as including those particles between 0.3 to 2.0 µm (channels 0.3, 0.5, 0.7, and 1.0), while coarse particulates are greater than 2.0 µm (channels 2.0 and 5.0). Particle counts are presented as "box and whisker" plots using Microsoft Excel software (Hunt, 1996). The plots provide a simple graphical summary of a data set, showing a measure of central location (median) and two measures of dispersion (range as indicated by the whisker, and inter-quartile range as indicated by the box). Particle counts are also presented on IKONOS imagery using ARCVIEW 9 software.

The laser particle counter was used to sample particulates in Bangkok, Thailand (13 sites along the heavily-travelled Silom Road, January 19, 2007) and Phoenix, Arizona (12 sites from various locations across the city, January 21, 2004 (Saleh, 2004)). The counts are not intended to represent average conditions for these two cities; rather they are used here to provide an initial comparison to counts taken in Phnom Penh. Bangkok offers a comparison with a well-developed Southeast Asian city, and Phoenix offers a North American city in a desert environment (dry conditions) with a population comparable to Phnom Penh's (1.3 million). The significance of the counts was determined by a two-tailed, unpaired T-test (Excel Software) at a 5% level of confidence.

Results and Discussion

City-Wide Counts

The median Phnom Penh city-wide fine particle count (not including counts from the city dump) is $1.07 * 10^8$ (Figure 2), accounting for 97% of the total particle count. The mean count is $1.08*10^8$, suggestive of a data set with a normal distribution. The median and mean fine particulate count for Phnom Penh is less than that of the larger city of Bangkok ($1.41*10^8$ and $1.42*10^8$, respectively) but exceeds that for Phoenix ($3.75*10^7$ and $4.04*10^7$, respectively) – each cities fine coarse count is significantly different from the other. This was not surprising given the larger volume of traffic in Bangkok, and the greater emissions controls in Phoenix. Phnom Penh's greater range and inter-quartile range, as compared to the other two cities, reflects a greater number and variety of counting sites included in the Phnom Penh data set.

The median Phnom Penh city-wide coarse particle count is $1.36*10^6$ (Figure 3). An examination of Phnom Penh's coarse particle box and whisker plot (Figure 3) shows a dataset skewed toward a number of sites with a disproportionate number of high counts. This is reinforced by a mean coarse particle count ($2.95*10^6$) that is two times its median count (off centre and skewed toward the high counts). The skewed data suggests a number of strong sources for re-entrained coarse particles (dust) or "hot spots" within the city. In other words, the high coarse particle counts are driven, at least in part, by a few very dusty sites. Phnom Penh's median coarse particle count is two-times greater than Bangkok's (mean = $7.75 *10^5$) and an order of magnitude greater than counts in Phoenix (mean = $4.87 *10^5$). While Phnom Penh's coarse particle count is significantly different from the other two cities, the coarse counts for Bangkok and Phoenix are not significantly different from one another. While most main streets in Phnom Penh are now paved, this has only occurred recently and many side streets are still unpaved. In addition there is a large amount of

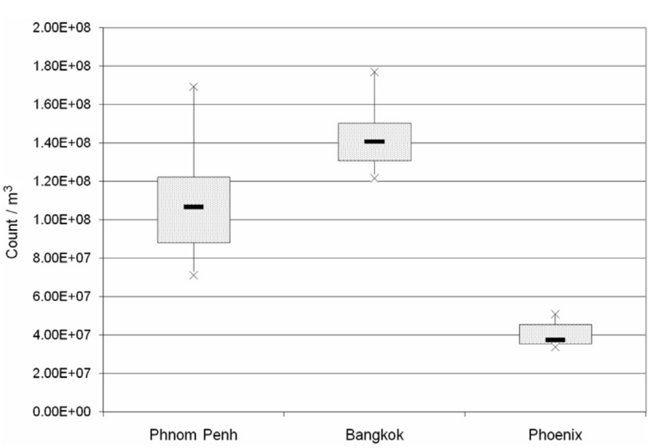

Figure 2: Phnom Penh's fine particle counts, with a comparison to other cities.

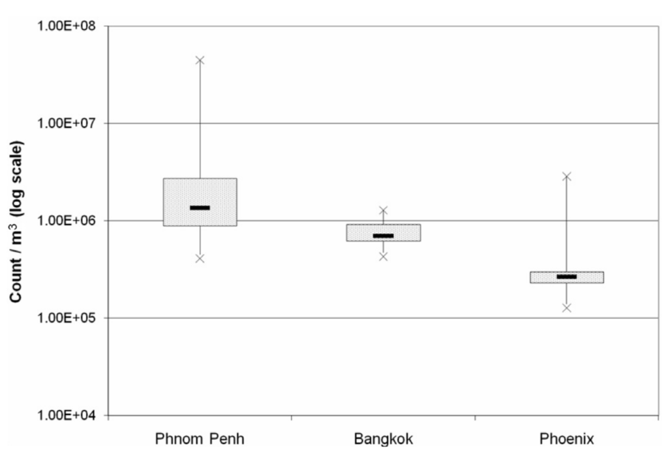

Figure 3: Phnom Penh's coarse particle counts, with a comparison to other cities.

roadwork and construction as the city develops. Thus, it is unsurprising that coarse dust levels are relatively high.

An examination of air pollution counts from Beijing, China (Tang, 2008) shows our counts to be comparable. While the Beijing fine particle counts include only those particles less than and equal to 1.0 µm (as compared to 2.0 in this study), the mean count of $1.2*10^8$, likely to be greater if the 1.0 to 2.0 µm size ranges were included, is comparable to Bangkok's 1.42 $*10^8$ count. Beijing's mean coarse particle counts, which include only those particles greater and equal to 3.0 µm (as compared to 2.0 microns in this study), are $1.43*10^6$. This count, likely to be greater if the 2.0 to 3.0 µm size range were included, exceeds that of Bangkok (7.75 $*10^5$) but is less than for Phnom Penh (2.95 $*10^6$).

While only a handful of sites were counted for airborne particles in rural Cambodia, a comparison with the Phnom Penh counts provides a useful perspective. Fine particle counts along a rural Cambodia road in Srae Ronoung commune, Takeo Province ($4.07*10^7$) were 38% of the median value in Phnom Penh, and counts at sites removed from the immediate influence of villages and roads ($1.59*10^7$) were only 15% of median Phnom Penh counts. Coarse particle counts along the rural Cambodia road ($9.16*10^5$) were 67% of the median value in Phnom Penh, and counts at sites removed from the immediate influence of villages and roads ($2.60*10^5$) were even lower, at 19% of median Phnom Penh counts. Without reading too much into the small number of samples collected in rural Cambodia, it is safe to state that median particulate concentrations in Phnom Penh are two to three times higher than any counted along rural roads, and about six times higher than any counted from a rural field. Individual sites in Phnom Penh show coarse particle counts that exceed rural counts by over an order of magnitude.

Road Surfaces

A breakdown of Phnom Penh particulate counts by road surface type reveals a slightly and significant higher median count of fine particulates on paved ($1.69*10^8$) than on dirt roads ($9.21*10^7$) (Figures 4 and 5). This increased count may be attributed to greater traffic volume on the paved roads. The coarse particulate counts show a substantial and significant difference between paved and dirt roads ($1.28*10^6$ vs. $1.93*10^7$) with dirt roads showing median coarse particle counts 15-times greater than those measured along paved roads.

Dry versus Wet Season

The re-sampling of 33 sites during the summer rainy season (June 19, 2007) showed a significant drop in particulate counts from winter dry season counts. Median fine and coarse particulate counts dropped by 22% and 37%, respectively. While both fine and coarse particle counts dropped, the fine particle counts appeared to have dropped across a wide range of re-counted sites (both high and low initial counts), as the mean dropped by only 14%. A drop in mean coarse particle counts of 55% suggests that wet roads and a shorter length in dry antecedent periods substantially limited the entrainment of coarse particles at sites with initial high counts or hot spots (Figure 6).

Site-Specific Particle Counts

City-wide distributions of particulate counts in Phnom Penh during the dry season (city dump counts were taken during the wet season) are presented in Figures 7 and 8. The lowest count of fine particles is apparent along the

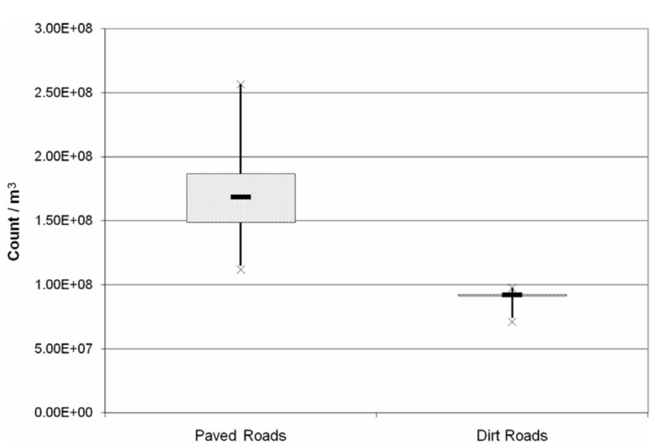

Figure 4: Phnom Penh's fine particulate counts by road surface.

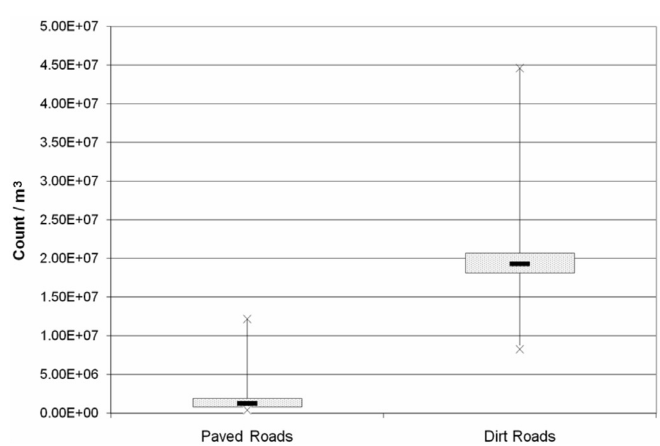

Figure 5: Phnom Penh's coarse particulate counts by road surface.

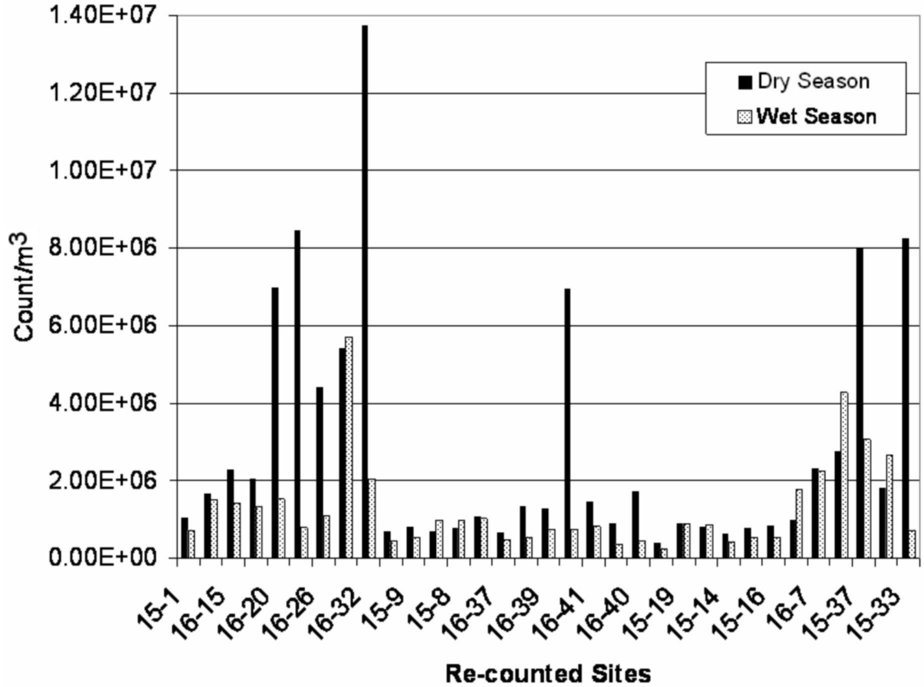

Figure 6: Coarse counts at re-sampled sites.

water front (Figure 7) where winds were light and out of the northeast. High counts appear across the city, with higher counts being associated with increased traffic volume (e.g. major roadways and intersections). In addition to the water front, lower counts occur on dirt roads (area B, Figure 7) and sites located on the city's edge (e.g. sites on the west and southwest edge of Phnom Penh), likely due to lower traffic volume. The low counts at the city's dump (area C, Figure 7) may be somewhat surprising given the continued burning of trash at the dump site. However, the smoldering fires at the dump burn at low temperatures thus producing more smoke (coarse particles) than fine emissions more typical of higher temperature emission sources (e.g. vehicle emissions).

As with fine particle counts, the lowest concentration of coarse particles occurs along the waterfront, but counts are also low within the city proper (Figure 8). The low levels may be attributed to the absence of dust sources (fewer dirt roads), and also to high traffic volumes that keep dust from accumulating on well-travelled streets (streets are literally swept clean by a large number of passing vehicles). In addition, the city employs people to sweep the streets, which helps to prevent the buildup of dirt. High coarse particulate counts occur at isolated sites (e.g. dirt covered roads in area B, Figure 8) and along the less developed south and southwest edge of the city (greater number of dirt roads or dirt covered paved roads), as well as at the city dump (area C, Figure 8). While the coarse particles at the dump are smoke, the counts are similar to airborne coarse particle counts taken along some of Phnom Penh's streets. An illustration of the local nature of hot spots can be found along a transect (area A, Figure 8) taken along a paved road from the Central Market to the water front. The second site from the river shows a substantially higher coarse count than that of other sites along the paved road. The higher count is attributed to a dirt street intersecting the paved road.

Conclusion

The median Phnom Penh city-wide fine and coarse particle counts are $1.07*10^8$ and $1.36*10^6$, respectively. While the fine count exhibits a normal distribution, the coarse particle count is skewed towards higher counts. The fine particle counts appear to be driven by traffic volume and are more evenly distributed across the city whereas the high coarse particle counts are localized and driven, at least in part, by a few very dusty sites. The even distribution of the fine particle counts and the localized nature of the hot spots are clearly evident when mapped. A breakdown of Phnom Penh's particulate counts by road surface type reveals a slightly higher median count of fine particulates on paved ($1.69*10^8$) than on dirt roads ($9.21*10^7$). The coarse particulate counts show a substantial difference between paved and dirt roads ($1.28*10^6$ vs. $1.93*10^7$), with dirt roads

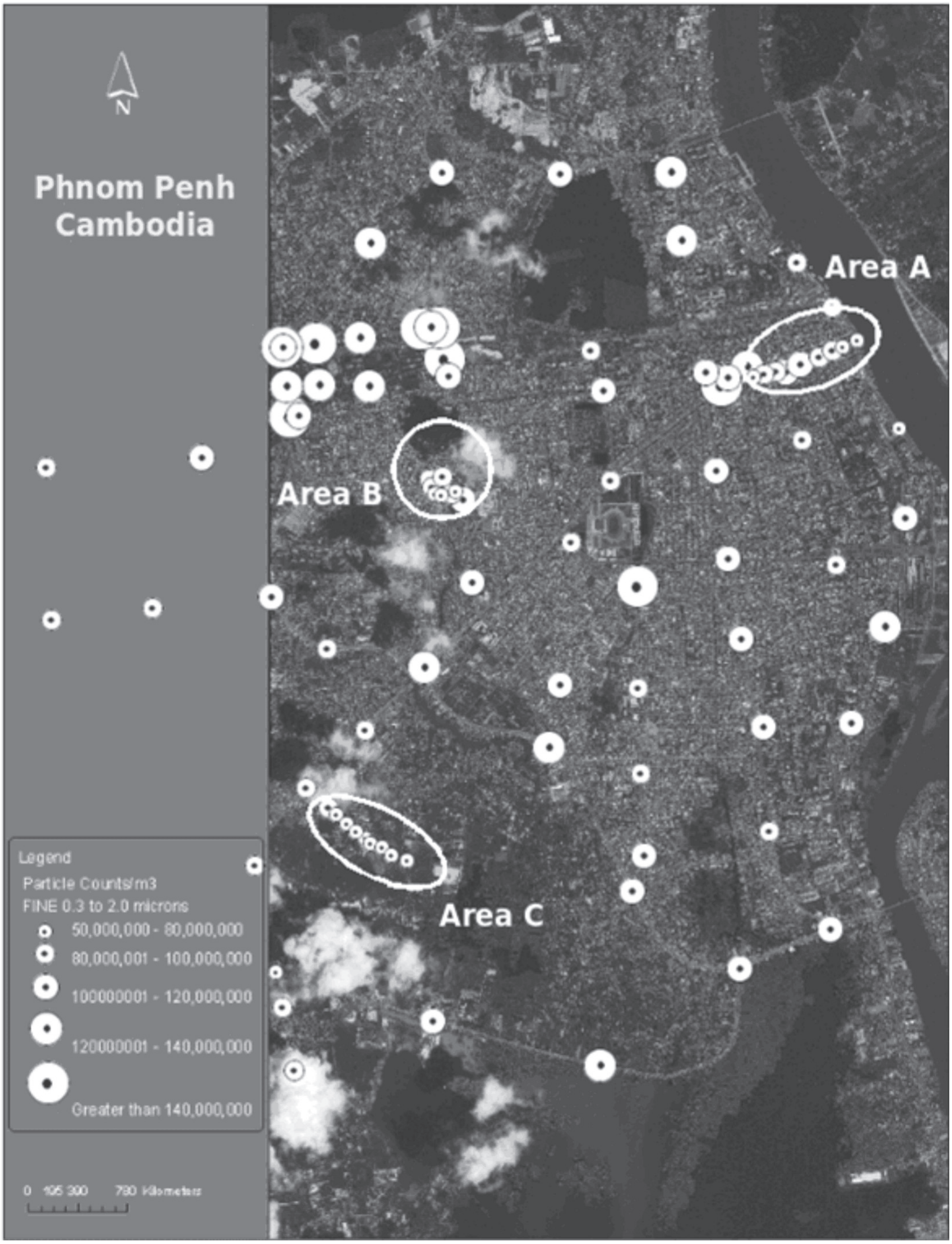

Figure 7: Phnom Penh site-specific fine particle counts.

showing median coarse particle counts 15 times greater than those measured along paved roads. A comparison of counts between seasons shows an overall decrease in airborne particulates during the wet season. The fine particle counts appeared to have dropped across the board (high and low initial counts) whereas the coarse particle counts dropped predominately at sites that reported high counts (hot spots) during the dry season.

With the exception of Bangkok's fine airborne particulate counts ($1.41*10^8$), fine and coarse particle counts in Phnom Penh exceed the comparison cities. The large amount of open burning at the municipal dump was not associated with fine particulate counts, but did produce locally high coarse particle counts.

Management of airborne fine particulates will require controls on traffic volume and related emissions – more

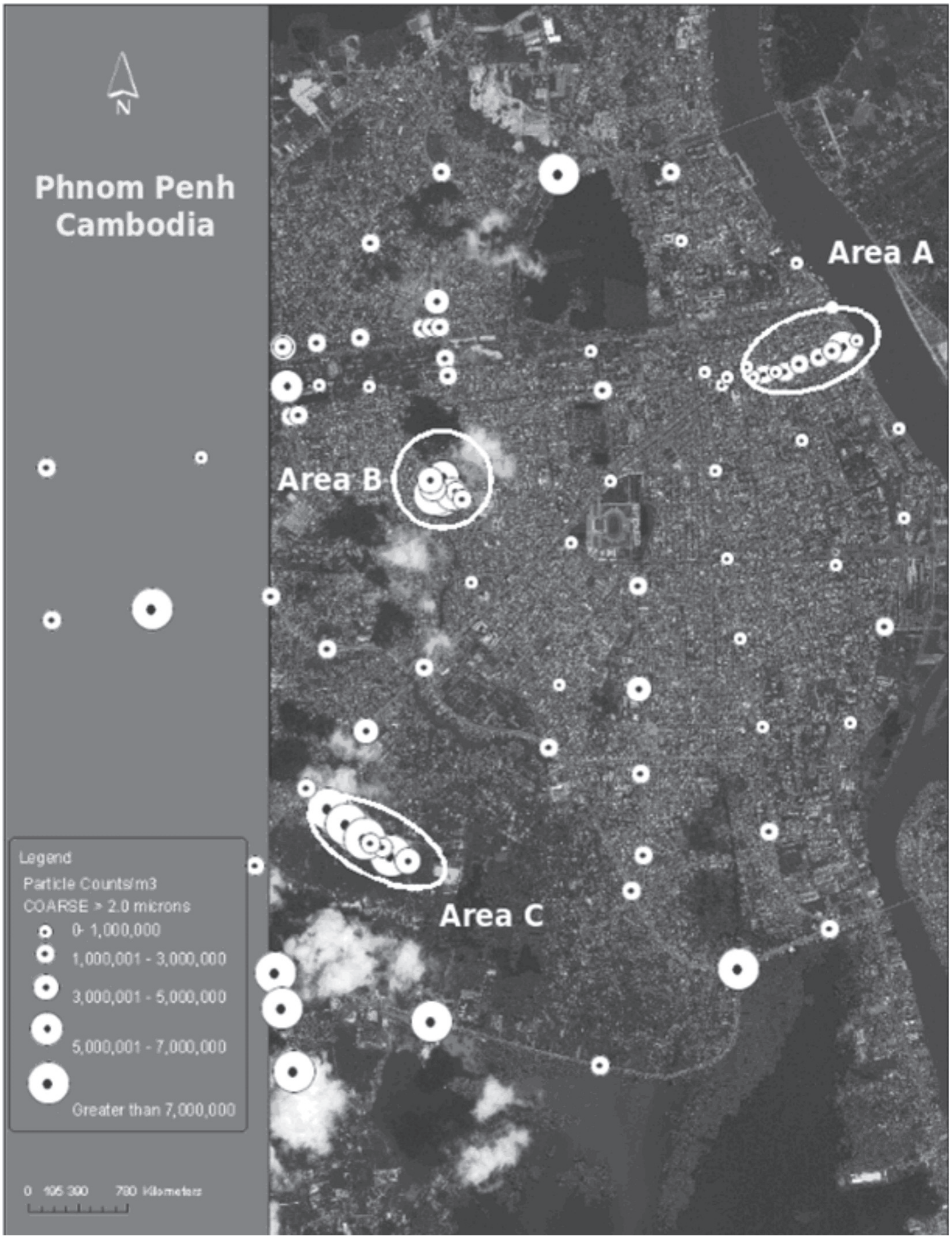

Figure 8: Phnom Penh site-specific coarse particle counts.

efficient motodop engines and freer flowing traffic. The paving of targeted city roads, along with efforts to keep dust from shoulder areas from coating paved roads, will profoundly reduce airborne coarse particles in the city. These data provide an important city-wide baseline, which will allow comparison of particulate pollution change as traffic volume and traffic flow change, and as city road surfaces continue to be paved.

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Contents