Correcting respirable photometric particulate measurements using a gravimetric sampling method

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Abstract

According to the National Environmental Management: Air Quality Act of 2004 people have the right to clean air and a healthy environment. Particulate matter (PM) emissions pose a significant health threat. Both indoor and ambient air pollution contribute to the burden of disease associated with poor air quality. This is particularly true within the South African setting where low income households make use of different solid fuels for heating and cooking purposes resulting in high levels of PM emissions. This paper focuses on the evaluation mass concentration measurements recorded by continuous photometric PM instruments within KwaDela, a low income settlement in Mpumalanga located on the South African Highveld. Thus, obtaining a photometric calibration factor for both the DustTrak Model 8530 and the SidePak AM510. Sampling took place during August 2014 for a period of seven days. The photometric and gravimetric instruments were collocated within the indoor environment of selected households. These instruments were all fitted with 10mm Dorr-Oliver Cyclone inlets to obtain the respirable (PM_4) cut-point. The study found that both instruments tend to overestimate the indoor particulate mass concentrations when compared to the reference gravimetric method. The estimated photometric calibration factors for the DustTrak Model 8530 and SidePak AM510 are 0.14 (95%Cl: 0.09, 0.15) and 0.24 (95%Cl: 0.16, 0.30) respectively. The overestimation of the photometric measurements is rather significant. It is therefore important that the correction factors are applied to data collected in indoor environments prone to the combustion of solid fuels. The correction factors obtained from this and other studies vary as a result of the environment (ambient, indoor etc.) as well as the aerosol size fraction and the origin thereof. Thus, it is important to considered site specific calibration factors when implementing these photometric light-scattering instruments.

Keywords

respirable particulate matter, gravimetric analysis, light scattering photometer, photometric calibration factor; indoor air quality

Introduction

According to the World Health Organisation (2006) having access to air of good quality is necessary for a healthy life, this statement is supported by the South African National environmental management: Air Quality Act 39 of 2004. However, air pollution continues to be a major health problem globally, causing an estimated seven million premature deaths a year. The majority of these deaths are associated with the populations of developing countries (WHO, 2014).

The 2010 Global burden of disease study indicated that an estimated 3.5 million (uncertainty level: 2.7, 4.5) premature deaths are caused by household solid fuel use, an additional 0.5 million deaths can be attributed to ambient air pollution resulting from household emissions (Bruce et al., 2015). It is thus no surprise that the study rated ambient air pollution as the ninth and indoor air pollution as the third leading risk factors associated with the global burden of disease (Lim et al., 2012).

Recently focus has been drawn to the significance of indoor exposure to PM as most people tend to spend more than 85% of their time indoors (Yassin et al., 2012; Funk et al., 2014). Most data collected on PM concentrations are based on ambient measurements, which is not a reliable indicator of the particulate levels associated with indoor and personal exposures (Huang et al., 2007).

Measuring of particulate mass concentrations, which is the most widely reported parameter, is conducted mainly for scientific and regulatory reasons (McMurry, 2000).

The WHO and South African National Ambient Air Quality Standards (NAAQS) have set guidelines for exposure to PM_{10} and $PM_{2.5}$. The exposure guidelines for the annual and 24-hour averaging period for both PM_{10} and $PM_{2.5}$ are represented in Table 1. There is a significant difference between the WHO and NAAQS as the guidelines set by the WHO are much lower than those set by the NAAQS. It is important to note that there are no set guidelines for indoor PM exposure as the South African guidelines focus on ambient exposure. There is, however, not a set guideline for the respirable particulate fraction (PM_4) investigated in this study.

***Table 1**: WHO and NAAQS*

		24 Hour (µg/m³)	1 Year (µg/m³)
PM_{10}	**WHO**	50	20
	NAAQS	75	40
$PM_{2.5}$	**WHO**	25	10
	NAAQS	65	25

Source: South Africa (2009 & 2012) and WHO (2006).

Ground-based PM monitoring is usually performed by using either continuous measurements collected by real-time PM monitoring instruments or filter-based manual sampling methods (Engel-Cox et al., 2013). The filter-based sampling method is a time integrated method obtaining PM mass concentrations through direct measurements, whereas the continuous instruments are based on various technologies and considered as an indirect measurement method. Continuous monitoring measurements make it possible to gain insight into levels of PM during shorter time intervals (Tasić et al., 2012).

Light-scattering photometers, such as the DustTrak Model II 8530 and SidePak AM510 (TSI Inc., Shoreview, MN, USA), are commonly used to measure PM mass concentrations (TSI Inc., 2002; Kim et al., 2004; TSI Inc., 2014). Previous studies done relating to the DustTrak (Tung et al., 1999; ; Heal, et al, 2000; Ramachandran, et al, 2000; Chung, et al, 2001; Yanosky et al., 2002; Braniš and Hovorka, 2005; Kingham, et a., 2006; McNamara et al., 2011; Wallace, et al, 2011) and SidePak (Thorpe, 2007; Zhu et al., 2007; Jiang, et al., 2011; TSI Inc., 2013) photometric aerosol monitoring instruments have indicated a significant overestimation of the particulate concentrations when compared to a reference gravimetric method. These studies were all conducted in various settings and compared to different reference methods. It is therefore critical to estimate a calibration factor for each monitor within the specific sampling environment.

The aim of this study was to evaluate and obtain a photometric correction factor for two indoor photometric monitoring instruments, DustTrak II Model 8530 and SidePak AM510, situated within a South African low-income settlement prone to the indoor combustion of low-grade solid fuels, such as coal and wood.

Material and Methods

Experimental Design

The results presented in this article are part of a larger study on the measurements of ambient and indoor exposures experienced in a typical low-income settlement in South Africa. KwaDela (26°27'47.53"S; 29°39'51.73"E) is such a low-income settlement located in the Mpumalanga Highveld, part of the Highveld Priority Area, approximately 200 km South-East of Johannesburg. The settlement is somewhat isolated, the closest town being Bethal, which is ~25 km West of KwaDela. A significant proportion of the settlement relies on the burning of solid fuels as their primary energy source used for everyday activities such as space heating and cooking. An evaluation of indoor PM_4 has been done for a one week period in August 2014. During the sampling period ambient air temperatures averaged around 12°C (low 3°C, high 25°C) while an average relative humidity of 64% was experienced.

From these twenty sampling houses two were randomly selected for the comparison study. The PM_4 measurements were collected by making use of both photometric direct-reading instruments and a gravimetric sampling method.

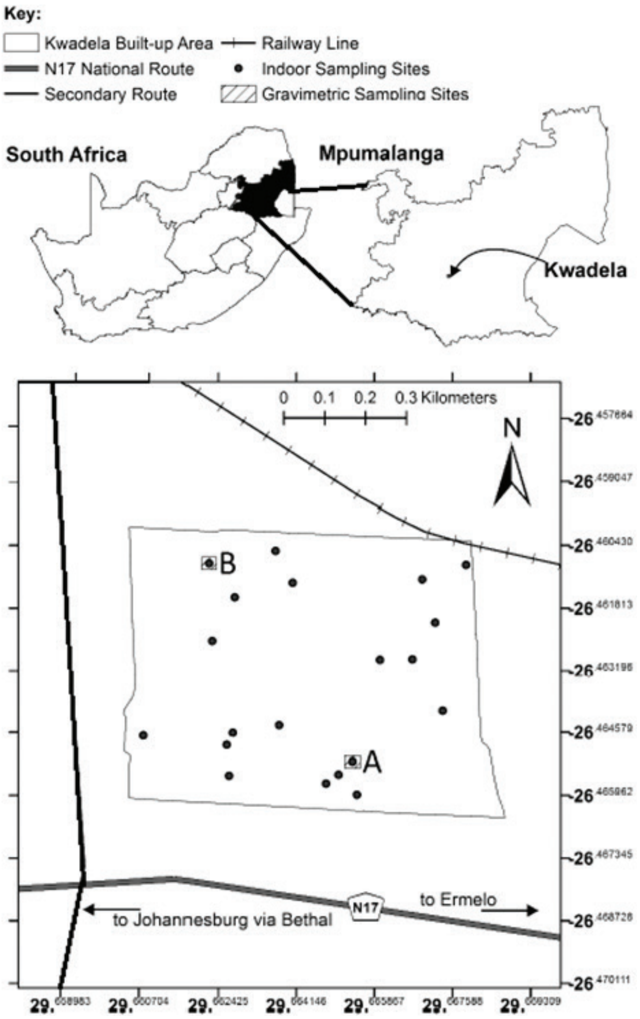

***Figure 1**: KwaDela low-income settlement in Mpumalanga, South Africa. The spatial distribution of the indoor and gravimetric sampling sites are also represented.*

Continuous Monitoring Instruments

PM_4 concentrations in indoor air has been measured using two photometric light scatting monitors, namely the **DustTrak II Model 8530** and **SidePak AM 510** (TSI Inc., Shoreview, MN, USA). These instruments do not have a built in PM_4 impactor, thus a **10-mm Nylon Dorr Oliver Cyclone** inlet (TSI Inc., Shoreview, MN, USA) was used with each instrument. The instruments were sampled at a flow rate of 1.7 L.min^{-1}, to acquire the required 50% cut size at 4 µm (the cyclone removes 100% of 10 µm particles and 50% of 4 µm particles, this in turn resembles the 0% of 10 µm particles and 50% of 4 µm particles which enter the lung (Sensidyne, 1999)). The DustTrak operated for 24 hours a day, in 12 hour intervals from 10h00 to 22h00 and again from 22h00 to 10h00. The SidePak operated for 12 hours a day, in 6 hour intervals from 10h00 to 16h00 and again from 16h00 to 22h00.

These specific sampling times were chosen as to avoid a sample collecting PM over both peak burning period found in the settlement; which could result in filter overloading. PM_4 concentrations were logged in five minute intervals. The output for the particulate mass concentration was given in milligram per cubic meter (mg.m^{-3}) (TSI Inc., 2002; Kim et al., 2004; TSI Inc., 2014). By averaging the five minute interval concentrations over the sampling duration, the time-integrated measurement were calculated (Kim et al., 2004). Data was downloaded from the instruments at the end of each sampling event, by connecting the instrument via a USB connection to a computer, using the TSI TrackPro Software. Table 2 gives the manufacturer's specification for both the DustTrak and the SidePak photometric monitoring instruments.

***Table 2**: Manufacturer specifications for the photometric instruments*

	DustTrak II 8530	**SidePak AM510**
Flow Rate (L/min)	1.7-2.4 (1.7)	0.7-1.8 (1.7)
Particle Size Range (µm)	0.1 - ±10	0.1 - ±10
Mass Concentration Range (mg/m³)	0.001-100	0.001-20
Laser Beam Wavelength (nm)	780	670
Operating Temperature (°C)	0 - 50	0 - 50
Temp. Coefficient (mg/m³ per °C)	+0.001	+0.0005
Zero Stability (mg/m³) over 24-hr at 10 second time-constant	±0.001	±0.001
Calibration	Arizona Test Dust	Arizona Test Dust

Source: TSI Inc. (2002 & 2014).

Gravimetric Sampling Method

The gravimetric sampling was done by exposing 37mm cassettes, at a constant flow rate of 1.7 L.min^{-1}, using Gilian GilAir 3 (Sensidyne, Clearwater, FL, USA) pumps. The pumps were fitted with 10-mm Nylon Dorr Oliver Cyclone inlets to obtain the 50% cut size at 4 µm. The gravimetric sampling occurred in line with the photometric monitors. Thirty-seven millimetre Borosilicate Microfiber Filters (ADVANTEC MFS Inc., Pleasanton, CA, USA), used in the 37 mm cassettes, were weighed prior to and after sampling. Weighing was done by making use of a XP26 DeltaRange Microbalance (Mettler-Toledo AG, Greifensee, CH) having a sensitivity of 1µg.

Photometric Calibration Factor

The PM_4 photometric measurements could be adjusted by making use of a calibration factor to approximate the actual PM_4 mass concentration. By doing a comparison between the PM_4 mass concentrations obtained from the photometric monitors and the reference gravimetric method a specific calibration factor was developed for each instrument. The calibration factor was calculated by the following equation (4):

$$Cal.Factor = \frac{Grav.Conc.}{Inst.Conc.}(Cur.Cal.Fac.) \qquad (1)$$

The DustTrak and SidePak measurements were then corrected by multiplying the five minute averages with the specific photometric calibration factor assigned to each instrument.

Quality Assurance and Quality Control

Various procedures were integrated into the sampling to ensure the quality of the photometric measurements. Preceding the start of the sampling campaign the monitors were sent for factory calibration using the respirable fraction of standard ISO 12103-1, A1 Arizona test dust. Before each sampling event the instruments were zero-calibrated by attaching the zero-filter as per the manufacturer's instructions. Flow rates were checked prior to and after each sampling event to ensure that the target flow rate was maintained. Filters were handled with care during weighing and loading activities as to prevent contamination and loss of gained PM and insure filter weight accuracies. The micro-balance was situated in a clean-lab, having controlled access, to limit external interference during weighing. The balance was levelled and calibrated, with the weights provided by the manufacturer, prior to each weighing session. It also has an internal function that removes any static that might influence the mass measurements.

Statistical Analysis

Basic statistical analyses were performed by using STATISTICA version 12 (StatSoft Inc.). All statistical analyses were performed with a 0.95 confidence and a 0.05 significance. The correlation coefficient analyses was performed to indicate the direction and strength of the linear relationship between the concentrations obtained from the real-time photometric instruments and gravimetric sampling. Furthermore, comparisons were made between initial and corrected PM_4 mass concentrations (one day case study) as well as cumulative distributions for a one week period.

Results and Discussion

Photometric Calibration Factors

Twenty-eight sets of comparison samples were collected during a week sampling in August 2014. A total of seventeen sets were valid, eight sets contributing to the evaluation of the DustTrak and nine to the evaluation of the SidePak. The other eleven sets were voided due to the loss of filter mass during gravimetric sampling (8), SidePak monitor experiencing a battery failure (1), and incorrect flow rates (2).

The linear regression for the 12-hour integrated DustTrak concentrations against the 12-hour gravimetric concentration resulted in a correlation coefficient (r^2) of 0.79, which gives an indication that the DustTrak measurements have a strong positive correlation when compared to the gravimetric concentrations. The linear regression for the 6-hour integrated SidePak concentrations against the 6-hour gravimetric concentration data resulted in a correlation coefficient (r^2) of 0.64, indicating a moderate positive correlation. In addition, an analysis was done of the ratio of the 12-hour integrated DustTrak concentrations and 6-hour integrated SidePak concentrations against the 12- and 6-hour gravimetric concentrations. The median ratio value for the DustTrak is 11.54 (low 3.76, high 31.25) with a standard deviation of ±9.23, while the median ration value for the SidePak is 3.83 (low 1.11, high 19.80) with a standard deviation of ±6.49. An average ratio of 7.32 and 4.16 existed between the DustTrak and SidePak and their respective gravimetric concentration. The ratios for the both these instruments vary dramatically from one day to the next. This may indicate that there is a significant variation in the day-to-day variability within a single household.

The estimated photometric calibration factor for the DustTrak is 0.14 (**95%Cl**: 0.09, 0.15) whereas the SidePak has an estimated calibration factor of 0.24 (95%Cl: 0.16, 0.30). The DustTrak calibration factor is significantly lower than those produced by previous studies. The SidePak calibration factor, while not identical to previous studies is slightly lower. The differences could be due to various aspects such as (1) having a reduced sensitivity when measuring lower PM concentrations (Jimenez et al., 2011), (2) the variations in chemical composition of aerosols and the type of aerosol (Jiang et al., 2011), (3) the difference in density between Arizona test dust and the type of aerosol measured, combustion aerosol tend to have a lower density than the test dust (TIS Inc., 2013), (4) the effect of temperature and relative humidity (McNamara et al., 2011), and (5) the different size fractions associated with aerosols (Yanosky et al., 2002).

Cumulative Distribution

The initial and corrected PM_4 data shows the cumulative exceedances (Table 3) of all WHO and NAAQS standards are similar for both the DustTrak and SidePak instruments. Initial (DustTrak and SidePak) measurements exceed the 75 µm/m³ NAAQS PM_{10} level for 35% and 28% of observed measurements, while the corrected measurements exceed the level for 5% of the observed measurements. The highest level of cumulative exceedances are of the 25 µm/m³ WHO $PM_{2.5}$ level. This level is exceeded for 92% and 100% of the observed measurements, while the corrected measurements exceed the level for 10% and 18% of the observed measurements.

***Table 3**: Summary of the cumulative exceedances of PM_4 observed measurement concentrations for a one week period*

24 Hour (µg/m³)	DustTrak Model 8530		SidePak AM510	
	Initial	Corrected	Initial	Corrected
WHO $PM_{2.5}$	92%	15%	**100%**	18%
WHO $PM_{2.5}$	65%	8%	**68%**	10%
NAAQS $PM_{2.5}$	42%	6%	**35%**	6%
NAAQS PM_{10}	35%	5%	**28%**	5%

Conclusion

Due to the linear relationship between negative health effects and increased PM concentrations, this observation indicates that the residents within KwaDela are chronically exposed to high levels of PM_4.

The development of a PM_4 calibration factor for an indoor environment prone to the combustion of solid fuels, such as coal and wood, has implications for both scientific and regulatory studies especially with regard to epidemiological and exposure assessments.

Historically, researchers have made use of averaged 24-hour values to characterise and estimate exposures to PM levels. It is, however, possible to measure exposures over short-term periods by making use of real-time PM monitors. Light-scattering photometer instruments are advantageous to use for monitoring indoor PM_4 concentrations due to the fact that they provide real-time data giving us insight into short-term changes in exposure levels. These instruments are also portable and require that minor maintenance be done periodically, making it easy to deploy within an indoor monitoring network, especially one within a low-income settlement such as KwaDela. The estimation of calibration factors for indoor solid fuel combustion reinforces certainty in studies that utilise these real-time monitoring instruments intended for this purpose.

A specific calibration factor was estimated for the DustTrak (0.14) and SidePak (0.24). These calibration factors should primarily be utilised where DustTrak and SidePak monitoring is conducted to quantify PM_4 exposure within an indoor environment where solid fuel combustion takes place.

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