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Urban $PM_{2.5}$ concentrations in a small Colombian city and the impact associated with particle emissions generated by small-scale lime production

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RESUMEN

Las directrices más exigentes asociadas a partículas finas $PM_{2.5}$ publicadas recientemente por la Organización Mundial de la Salud también motivan a las ciudades pequeñas a evaluar los niveles de exposición. En este estudio se evaluaron las $PM_{2.5}$ en el municipio de Vijes, un importante centro de producción de cal ubicado en el Valle del Río Cauca, Colombia. El objetivo principal de esta investigación fue determinar los niveles de $PM_{2.5}$ en concentraciones de fondo urbano de la ciudad y estimar el aporte de las fuentes industriales ubicadas al oeste del área urbanizada. Esta evaluación de las concentraciones de $PM_{2.5}$ en una ciudad que no posee monitores de calidad del aire fijos, datos meteorológicos ni información sobre las fuentes de emisión, fue diseñada por ser conveniente y posible de realizar con un presupuesto muy limitado. Se instalaron cuatro sensores ópticos y una estación meteorológica de bajo costo durante dos campañas separadas, cada una de tres a cuatro meses de duración. Las mediciones de $PM_{2.5}$ se analizaron con el apoyo de datos meteorológicos y modelos de dispersión. Se encontró que los niveles medios de $PM_{2.5}$ de fondo en la zona urbana estaban por debajo del valor límite colombiano de 25 $\mu g\ m^{-3}$, en el rango de 14 a 19 $\mu g\ m^{-3}$ y con los niveles más bajos en el centro de la ciudad. El monitor ubicado en el occidente del casco urbano, más cercano a las plantas industriales, registró un nivel medio de 24 h alto cercano al valor límite nacional. Se estimó que la contribución industrial a las concentraciones de $PM_{2.5}$ a largo plazo en el entorno urbano de Vijes era de un máximo de 6 $\mu g\ m^{-3}$, es decir, una fracción menor a los niveles medios de $PM_{2.5}$ monitoreados en el entorno urbano. La contribución dominante a las concentraciones de $PM_{2.5}$ se atribuyó a otras fuentes antropogénicas dentro y al este de Vijes, como también a la concentración de fondo regional que caracteriza el valle del río Cauca al este de Vijes, donde la quema de caña de azúcar antes de la cosecha es común.

ABSTRACT

The stricter guidelines for fine particles $PM_{2.5}$ recently published by the World Health Organization also motivate smaller cities to assess the exposure levels. In this study, $PM_{2.5}$ was assessed in the municipality of Vijes, an important lime production center in the Cauca River Valley, Colombia. The main objective was to determine $PM_{2.5}$ concentration levels in the urban background of the city and to estimate the contribution from industrial sources located west of the urbanized area. The assessment of $PM_{2.5}$ concentrations in a city without fixed air quality monitors, meteorological stations, and information on emission sources, was designed to be expedient and possible to perform with a very restricted budget. Four low-cost optical sensors and one low-cost meteorological station were installed during two separate campaigns, each three to four months long. The $PM_{2.5}$ measurements were analyzed with the support of meteorological data and dispersion modeling. Mean levels of $PM_{2.5}$ in the urban background were found to be below the Colombian limit value of 25 $\mu g\ m^{-3}$, in the range of 14 to 19 $\mu g\ m^{-3}$, and with lower levels in the city center. The monitor located in the westernmost urban area, closest to the industrial plants, registered a high 24-h mean level close to the national limit value. The industrial contribution to long-term $PM_{2.5}$ concentrations in the urban background of Vijes was estimated to be within a maximum of 6 µg m^{-3}, i.e., a minor fraction of the monitored $PM_{2.5}$ mean levels in the urban background. The dominating part of the $PM_{2.5}$ concentrations could be attributed to other anthropogenic sources within or east of Vijes, as well as originating from the regional background concentration characterizing the Cauca River Valley to the east of Vijes, where pre-harvest sugar cane burning is common.

Keywords: fine particles, air pollution, low-cost monitoring, modeling, industrial impact.

1. Introduction

Exposure to fine particles $PM_{2.5}$ has been shown to contribute to increased cardiopulmonary and lung cancer mortality. Based on a recent review of the existing evidence of the health effects of air pollution, the World Health Organization (WHO, 2021) has recommended that $PM_{2.5}$ concentrations should not exceed 5 µg m^{-3} as an annual mean or 15 µg m^{-3} as a 24-h mean. A systematic review found seven studies in Latin America that showed that an increase of 10 µg m^{-3} in $PM_{2.5}$ concentrations was significantly associated with increased risk for both respiratory and cardiovascular mortality (Fajersztan et al., 2017).

Since 2018, Colombia's regulations have established that $PM_{2.5}$ levels should not exceed 25 µg m^{-3} as an annual mean and 37 µg m^{-3} as a 24-h mean. $PM_{2.5}$ has been monitored in the largest Colombian cities since 2011. A recent exposure assessment shows average $PM_{2.5}$ levels between 2011 and 2014 of 27.5 µg m^{-3} in Bogotá and 26.0 µg m^{-3} in Medellín (Rodríguez-Villamizar et al., 2018), i.e., they exceed today's national limit value for annual mean $PM_{2.5}$. Additionally, the Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) established that for two monitoring stations located in Bogotá, approximately 15% of the data collected between 2011 and 2015 corresponded to concentrations exceeding 40 µg m^{-3} of $PM_{2.5}$. Expressed as the Colombian air quality index, this corresponds to the category of "harmful to health" (IDEAM, 2016). Rodríguez-Camargo et al. (2020) presented a spatial analysis of $PM_{2.5}$ concentrations for the city of Bogotá, where an increase of 1.2% in cardio-pulmonary mortality in the short-term and 9% in the long-term could be estimated in areas of the city with high daily and annual $PM_{2.5}$ concentrations.

To assure a healthy environment, it is important to assess $PM_{2.5}$ in all Colombian cities. In small cities with lower traffic volumes, lesser $PM_{2.5}$ concentrations can be expected; nevertheless, there are other urban emissions due to residential and commercial activities, and also industrial processes that may contribute to important particle emissions. Cities situated within or close to industrial areas are frequently affected by atmospheric pollutants that negatively impact public health and ecosystems. However, air quality in smaller cities is rarely monitored because of their low population density compared to large cities, especially in developing countries. The Cauca River Valley (CRV) is an agro-industrial region in southwest Colombia (Fig. 1), where a large fraction of the land is devoted to sugarcane cultivation and the production of its derivatives. A recent analysis of the $PM_{2.5}$ aerosol composition in CRV (Mateus-Fontecha et al., 2022) showed a dominant fraction of organic matter (53%), both primary and secondary, followed by salts (20%, mostly ammonium sulfate), dust (9%) and elemental carbon (7%). The authors concluded that biomass burning was a persistent source, together with traffic and fuel combustion.

In the present study, we have analyzed the pollutant criteria for $PM_{2.5}$ in the municipality of Vijes, an important center for lime production within the CRV (Fig. 1). The production of lime is the primary basis of the economy and life of the Vijes municipality, located approximately 40 km to the north of Cali, the capital city of CRV and Colombia's third largest city. Nowadays, Vijes has a population of 11 010 inhabitants and 13 small-scale lime production ovens. The limestone ($CaCO_3$) of Vijes is located in the western mountains of the Andes mountain range, and has a marine origin, mainly from marine invertebrates with shells or limestone skeletons, such as corals, gastropods, and bivalves (Nivia-Guevara, 2001). The limestone, transformed into quicklime or calcium monoxide (CaO), has had several historical applications in the manufacture of the mortar used in the construction of both common houses and monumental buildings, highlighting in the latter case its use in temples, basilicas, bridges, and old legendary

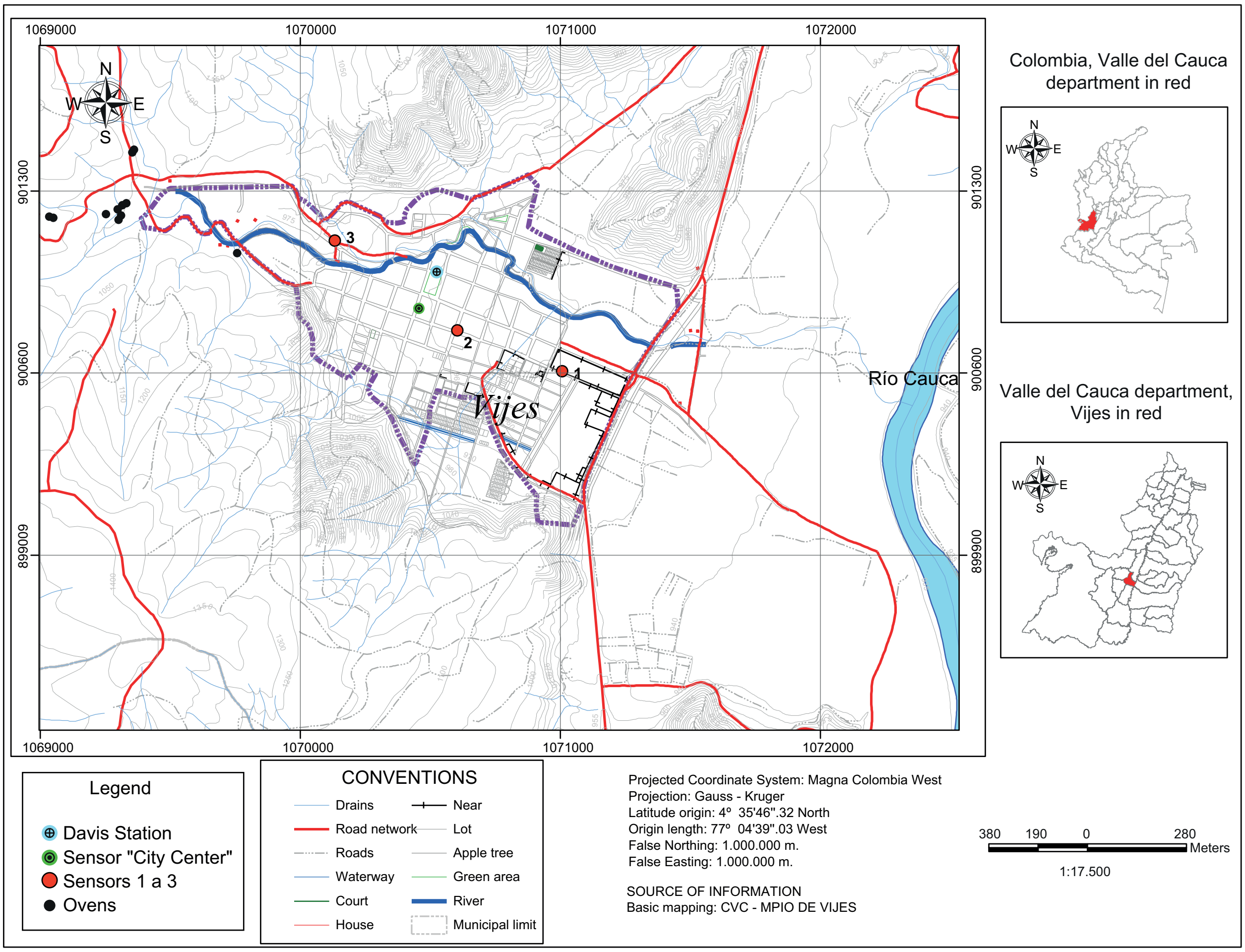

Fig. 1. Topographic map showing the location of the continuous furnaces, Vijes town center with four $PM_{2.5}$ monitoring points and the meteorological Davis station in the city center. The sole $PM_{2.5}$ sensor during the 2017 campaign is named City center. The three sensors of the 2019 campaign are named 1, 2, and 3. The smaller maps to the right show the Cauca River Department (top) and the Vijes municipality within the department (bottom).

houses in the CRV (Hincapié-Aristizabel et al., 2017). Subsequently, its usefulness was discovered in multiple industrial applications, e.g., in mills for the purification of sugar, in the paper industry, and for the treatment of water in aqueducts. The increased demand and production of lime gave employment and income to the citizens of Vijes and resulted in the city being known as the white town of the CRV. Although the fairly small lime production of Vijes plants only accounts for 3-4% of the lime used in the CRV, it is highly demanded in the area around Vijes.

Despite the fact that a wide variety of useful products with multiple applications is obtained from lime transformation, byproducts, and waste are also generated, some of them discharged into the air, soil, and to a lesser extent water. Atmospheric emissions generated by lime production ovens consist of both combustion gases and particles. Some of the emitted particles are characterized as fine and will thus directly contribute to increased $PM_{2.5}$ concentrations in the area. The main focus of this study was to determine the impact of lime production emissions on $PM_{2.5}$ concentration levels in the Vijes populated areas. For this purpose, we measured $PM_{2.5}$ concentrations with optical sensors and we registered meteorological variables using a meteorological station installed in a 15 m high tower in the city center. The meteorological measurements were aimed to determine the local wind patterns, but also to serve as input to a Gaussian dispersion model.

Historically, there were many older bee-hive ovens within and just outside Vijes, which employed a primitive technology that included the use of large amounts of firewood and charcoal (Hincapié-Aristizabel et al., 2017). However, since 2010 the regional environmental authority (Corporación Autónoma Regional del Valle del Cauca, CVC) has been pressing for the closure of the beehive furnaces located near or within populated areas, allowing the relocation of the industries to areas further away from the population. The authority has also forced the lime production industry to use continuous and less polluting technologies in the re-located ovens, in order to reduce the pollution impacts on the Vijes population. The present study thus had the purpose of evaluating the impact of lime production emissions on the Vijes air quality after the relocation and technical improvements of the plants, as enforced by the authorities.

Two $PM_{2.5}$ measurement campaigns were performed in Vijes, the first between December 2016 and April 2017, and the second between May and October 2019. An important objective of both measurements was to demonstrate the possibility of performing reliable $PM_{2.5}$ monitoring campaigns using low-cost devices that are easy to move around. The applicability of low-cost sensor technologies has been extensively reviewed (e.g., Morawska et al., 2018; Jayaratne et al., 2020; WMO, 2021). A general conclusion is a need to evaluate the performance of the particular sensor used, leaving recommendations on individual calibration against reference monitors. The procedure of calibrating a low-cost sensor by collocating it at the side of a reference monitor has been discussed in depth by Diez et al. (2022) and Liang and Daniels (2022). Low-cost and small sensors allow a huge number of devices to operate simultaneously, describing spatial patterns with great detail that traditional reference monitoring cannot accomplish, but they are also beneficial in low- and middle-income countries where few reference measurements are made (Giordano et al., 2021). The low cost of individual sensors implies that useful air quality assessments can be performed with a highly limited budget, a fact that allowed the present study.

Monitoring campaigns using various low-cost monitors allow for determining pollution levels and their distribution over the area of interest. However, they do not allow source attributions that pinpoint specific dominating sources to $PM_{2.5}$. In order to determine the role of the industrial sources west of Vijes as contributors to the $PM_{2.5}$ levels in the city, it was necessary to extend the methodology. This could be done by filter sampling $PM_{2.5}$ in the city, together with laboratory analyses to determine the composition of fine particles and finally perform some kind of receptor modeling. Since this is normally rather expensive, an alternative approach of an integrated monitoring and modeling assessment was used. With this, the industrial impact could be determined in a way more compatible with the low budget and the use of low-cost sensors.

Thus, the principal novelty of this study is the integrated use of $PM_{2.5}$ and meteorological data, supported by dispersion modeling. The methodology applied here can be used in urban settings where there is a lack of regular monitoring and little or no information on criteria pollutant emissions. It can determine if particle concentration levels are critical, need urgent actions to be taken, and also identify and quantify the contribution from specific emission sources associated with fine particulate matter.

2. Materials and methods

2.1 Design of the monitoring campaigns

The industrial sources of interest for the impact assessment were all located outside and to the west of the urbanized area of Vijes. This means they should impact the city in westerly winds conditions, most likely with somewhat higher impact in the western part of the urbanized area. The $PM_{2.5}$ sensors were situated in different parts of the urbanized area, at the top of buildings or at open terraces, to capture a representative urban background of $PM_{2.5}$ and face the influence from sources to the west without any physical obstacles in between. Two of the sensors were located in the city center ("City center" and 2), and the other two sensors were in the eastern (1) and western (3) periphery of the urbanized area (Fig. 1). The winds regulating the dispersion and dilution of air pollutants in Vijes were expected to be canalized up- and down-slope the mountain range, motivating the diagonal transect from sensor 1 to sensor 3. A representative meteorological measurement should preferably be located within the city, close to the $PM_{2.5}$ sensors, but at a sufficient height over the buildings to allow a more undisturbed wind regime.

The existence of a telecommunication tower at the police station in Vijes offered this possibility.

Due to limitations in human and economic resources, the measurements were performed as two separate campaigns. The first campaign was performed from January 28 to April 28, 2017, and involved only one sensor (City center). The second campaign took place between May 16 and October 25, 2019, involving three sensors (1, 2 and 3).

2.2 Monitoring of particulate matter

The detection technique using optical sensors was selected, considering the low cost of the devices and their portability. The latter characteristic facilitates their location at the most appropriate sites. In this study, the main objective of the monitoring was to capture $PM_{2.5}$ concentrations in the urban background of Vijes, representing typical exposure levels for the population. The sensors were mounted within a thermometric protection box, specially designed for this study. The purpose of the thermometric boxes was to avoid the sensors being heated by sun radiation and protect them from rain (Fig. 2).

Shinyei PPD42 is an inexpensive optical particle counter, in which the particles are dragged into a thermal plume provided by a resistance of 100 Ω, driven at 5 V × 50 mA = 0.25 W through a beam of infrared light (Allen, 2013). The particles that pass through the detection point scatter the light, then the receiver acquires the scattered light through the lens and transforms it into a pulse signal. The pulses per unit of time are proportional to the concentration of particles. Data from the four Shinyei optical sensors were stored in laptops and manually exported as hourly averages to an air quality management system (Airviro, 2022a) used as a research tool at the Universidad Autónoma de Occidente in Cali.

Fig. 2. Thermometric box used to protect the $PM_{2.5}$ sensors.

Before being placed in Vijes, the sensors were placed in parallel to reference monitors at an existing urban background station in Cali in order to be calibrated. The Shinyei sensor measurement is influenced by the location's specific conditions in terms of relative humidity and aerosol characteristics. These were considered to be similar in the urban backgrounds of Cali and Vijes.

During the monitoring campaigns, any anomalies in the immediate surrounding of the sensors were documented. A few hourly data were eliminated as the floor of the terrace where the sensor was located was swept.

2.3 Meteorological measurements

Considering that no specific meteorological information was available for the locality, a Davis Pro meteorological station was installed at a height of 25 m in the Vijes Police communication tower. The following variables were registered on an hourly basis: temperature, wind speed and direction, global radiation, humidity, and precipitation. For the data storage, the WeatherLink program was used with a data logger with a configurable storing interval from 1 to 120 min. Temperature, humidity, and global radiation were exported as hourly averages, while precipitation was accumulated to hourly totals. Wind speed and direction were exported as 15 min averages, using the last quarter of every hour as hourly data. Since wind direction were given as 16 wind sectors (N, NNE, NE…, etc.), each 15 min data were randomly given a specific degree (0º-359º) within the indicated sector. Calm conditions where no wind direction sector was given implied a data loss for that hour. More frequently, almost calm conditions were registered as zero in wind speed, but with a wind direction sector indicated. Those events were given a wind speed of 0.25 m s^{-1}. All meteorological hourly data were stored and analyzed in the Airviro system.

2.4 Dispersion model and emission inventory for industrial sources

For the urban scale modeling a Gaussian dispersion model was used over the Vijes area (approximately 4 × 4 km^2) with a spatial resolution of 25 × 25 m^2. The model is part of the Airviro system and incorporates a diagnostic wind model (Danard, 1977). This simplified model approach does not generate mass conservative wind fields but is able to describe the typical downslope/upslope winds during cooling/heating, as well as the local impact of different surface roughness on the wind field. Topography and surface roughness were given with a spatial resolution of 100 × 100 m^2. Meteorological input data with an hourly resolution were taken from the meteorological station located in the center of Vijes (see section 2.3). The dispersion model requires a determination of the atmospheric stability, which by default is calculated from measurements of wind speed and the vertical temperature gradient as recorded between 8 and 2 m height over the ground following the profile method outlined by Berkowicz and Prahm (1982). As it was not possible to obtain measurements of the vertical temperature gradient in Vijes, an empirical determination, elaborated in Chile, was used (Johansson et al., 2007). The empirical model covers four stability conditions and uses global radiation, wind speed, and temperature change from one hour to another as input data. Table I shows the details of the empirical determination of the vertical temperature gradient.

Emissions from industrial stacks, like the ones generated by the industrial sources west of Vijes, are then dispersed as Gaussian plumes following wind trajectories at a height determined by the stack height and a plume rise due to buoyancy and momentum forces. The calculation of the plume rise uses different formulas from the literature, depending on stability and wind speed, described in detail in the Airviro model documentation (Airviro, 2022b).

An emission inventory was created for the lime production plants west of the Vijes municipality, based on information collected during visits to and interviews with the plant owners of each plant, as well as from official statistics. In total, during the two monitoring campaigns there were 13 lime production units operating continuously in the uphill area to the west of Vijes (Fig. 1). Table II shows the characteristics of each unit, including the reported daily production. Assuming all units operate without filters or precipitators to control the emissions, emission factors from AP-42 (US-EPA, 1998) were applied, yielding 3.66 kg of emitted $PM_{2.5}$ per ton of lime produced. Table II shows the resulting emissions. The lime production was assumed to operate continuously all day long.

It was not possible to describe other anthropogenic and natural sources of $PM_{2.5}$ inside and east of Vijes. In the village center, one could expect (especially during daytime and evenings) particle emissions

Table I. Empirical determination of the vertical temperature gradient (diffT) between 8 and 2 m high provided by the model.*

	Condition (glob = rad intensity, *watt*/m^2)	diffT
1	Glob > 10	0.2116 – 0.001192*Glob
2	Glob <10 & (Temp[-1h] – Temp) > 0.5	0.5706 + 0.6112*(Temp[-1h] – Temp) – 0.3611*Wspeed
3	Glob < 10 & Temp[-1h] – Temp) < 0.5 & Wspeed > 2	Constant value = –0.06
4	Glob < 10 & Temp[-1h] – Temp) < 0.5 & Wspeed < 2	Constant value = 0.5

*Source: Johansson et al., 2007.

Table II. Characteristics of 13 industrial units located west of Vijes. The emission factor for $PM_{2.5}$ was taken from AP-42 (see section 2.4).

Source	Stack height (m)	Stack outer diameter (m)	Stack inner diameter (m)	Temp (°C)	Gas speed ($m\ s^{-1}$)	Production ($t\ day^{-1}$)	Emissions ($t\ year^{-1}$)
1	12	0.35	0.33	120	5	14	18.7
2	7	0.46	0.45	120	6	14	18.7
3	1	2.00	1.80	120	5	12	16.0
4	12	0.35	0.34	119	6	12	16.0
5	12	0.35	0.34	119	6	12	16.0
6	15	0.26	0.25	120	7	12	16.0
7	15	0.26	0.25	120	7	12	16.0
8	15	0.26	0.25	120	7	12	16.0
9	9	0.36	0.35	93	5	10	13.4
10	9	0.31	0.3	93	5	10	13.4
11	5	0.47	0.45	100	5	8	10.7
12	1	1.50	1.3	100	5	8	10.7
13	1	2.00	1.8	110	4	8	10.7

generated by road traffic exhausts and road dust (some road links unpaved), residential cooking and restaurants, and infrastructure like road maintenance and house constructions (the latter including the generation of both combustion and dust particles). One could also assume that polluted air should enter the Vijes urbanized area from the CRV to the east, where important particle emissions, not only from the principal road (which runs north-south in the valley just east of Vijes) with 10 000-11 000 vehicles per day but also from industrial and agricultural sources, occur nearby. The CRV is a center for sugarcane cultivation and pre-harvest burning of the fields is an important contributor to PM concentrations (Mateus-Fontecha et al., 2022).

3. Results

3.1 Intercalibration of optical sensors prior to the Vijes monitoring campaigns

Prior to their installation in Vijes, the $PM_{2.5}$ optical sensors were located side-by-side to reference monitors forming part of the Cali monitoring network. For the 2017 campaign (sensor City center) the intercalibration was performed through a comparison with data registered by a TEOM 1405 monitor located at an urban background station in the northern part of Cali and operated by the regional environmental authority CVC. For the 2019 campaign (sensors 1, 2, 3) the intercalibration was performed through a comparison with data registered by a BAM 1020 monitor located at an urban background station in the southern part of Cali and operated by the municipal environmental authority (Departamento Administrativo de Gestión del Medio Ambiente). Climate conditions in Cali and Vijes are very similar. Thus, the intercalibration followed the recommendation to place the low-cost sensors in close proximity to equivalent reference monitoring instruments, and in environmental conditions similar to those where the sensors are intended to ultimately operate (WMO, 2021).

Approximately five days of hourly $PM_{2.5}$ data, measured simultaneously with the Shinyei optical sensors and the reference monitors, were obtained and compared (Fig. 3). By using linear regression between the data obtained it was possible to find acceptable coefficients of determination (R^2 = 0.58-0.73) for three of the sensors. For sensor 2 the correlation was low (R^2 = 0.26) and the constant bias very high. The poor result of the calibration of this sensor, which also was the oldest device used both in the 2017 and 2019 campaigns, motivated its output to be excluded from further analyses. Since both sensor 2 and City center represented the conditions in the center of Vijes, the exclusion of sensor 2 did not seriously affect the further analyses and objectives of the study.

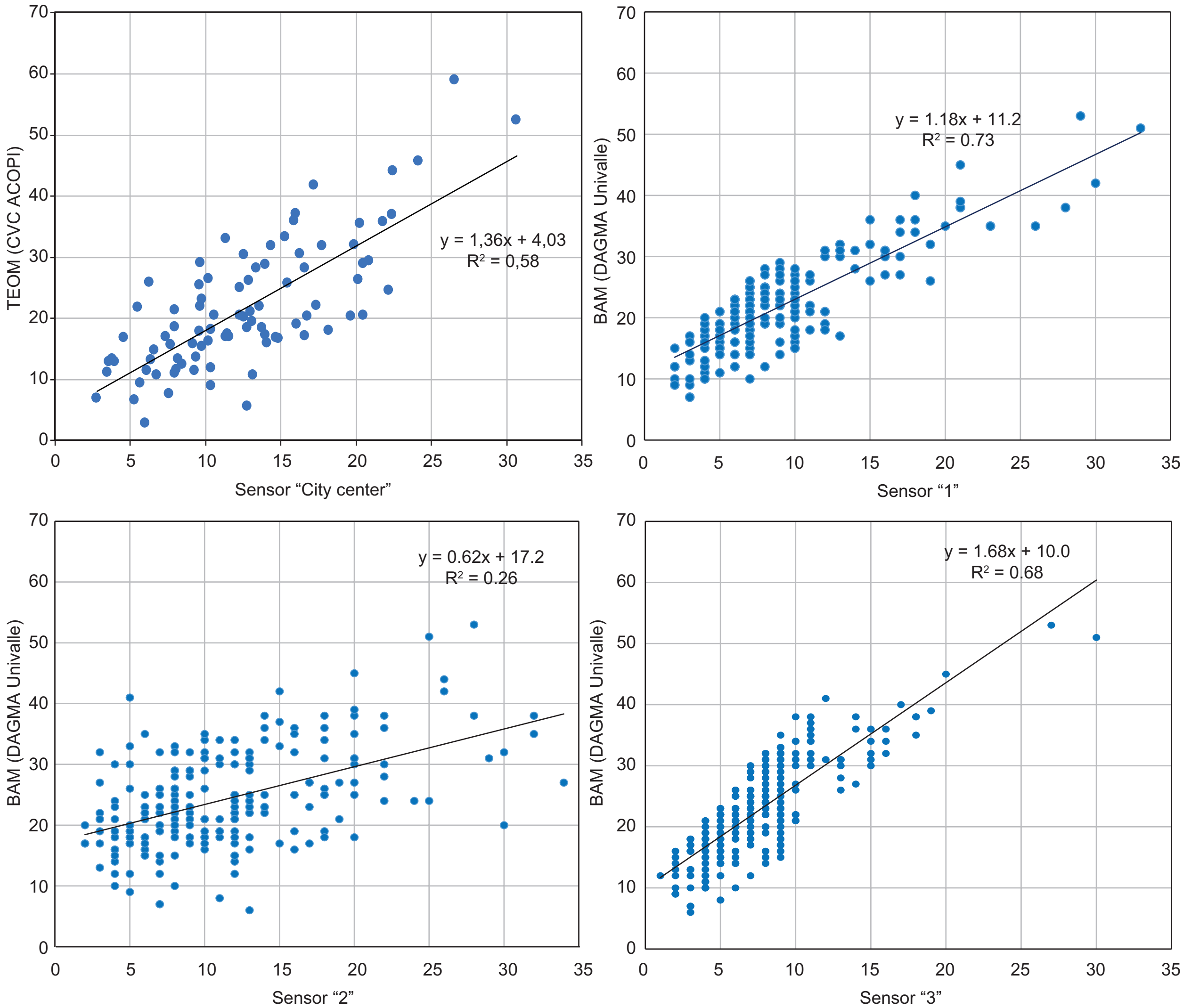

Fig. 3. Intercalibration performed as a comparison between hourly values as registered by the Shinyei optical sensors and the reference TEOM monitors installed in the ACOPI station in Cali (for sensor City center in 2017) and the BAM 1020 instrument installed at the Univalle station in Cali (for sensors 1, 2, and 3 in 2019). Units: µg m^{-3}.

The regression for the best fit between the low-cost sensors and the reference monitors, indicates a correction based on a slope (proportional bias) and an intercept (constant bias). An important characteristic of a correction applied to the low-cost sensors is to avoid any systematic underestimation of high particle concentrations. For sensors 1 and 3 the regression output (line in Fig. 3) seemed to work fine also at higher concentrations. For the sensor City center the regression line indicates a possibility of underestimated values for the highest hourly concentrations. However, since R^2 values only differed marginally (0.58 for the full regression with slope and a constant bias, 0.55 for a regression without a constant bias) and maximum hourly values only differed from 45.9 to 49.5, it was decided to use the correction with both a slope and a constant bias. The large constant biases of the sensors 1 and 3 indicate a high detection limit, i.e., that the monitors fail to register low concentrations < 10 µg m^{-3}.

3.2 Meteorological aspects

During the three-months monitoring campaign from January 28 to April 28, 2017 a failure in the

Table III. Meteorological data captured during the two campaigns.

	January 28-April 28, 2017	May 16-October 25, 2019	Units
N (hourly data captured)	1902	2221	hourly data
Mean temperature (max/min)	23.6 (31.3/17.4)	23.9 (32.8/8.5)	ºC
Mean wind speed (max/min)	2.2 (8.5/0.3)	2.2 (10.1/0.0)	m s^{-1}
Accumulated precipitation	24	500	mm
Mean global radiation (max/min)	212 (1200/0)	216 (1064/0)	W m^{-2}

meteorological station implied data losses from the March 22 to April 1. Also, during the second campaign between May 16 and October 25, 2019 there were data gaps due to technical problems, the larger from July 25 to August 22 (during which the $PM_{2.5}$ measurements were also lost). The results of all valid meteorological data presented here are compiled in order to compare the two campaign periods from a meteorological perspective and thus are not the same that will be used for the analysis of the $PM_{2.5}$ monitor data.

Table III shows that the two campaigns captured about the same amount of data, with similar averaged temperature, wind speed and global radiation. However, the first campaign took place during a very dry period, and the second with more precipitation. The CRV region has statistically two more rainy periods, March-May and October-November, however year-to-year variations are large.

The wind conditions are of key importance for how the industrial emissions west of Vijes impact the urbanized area. Figure 4 shows the pronounced daily variation of wind speed with a minimum of < 1 m s^{-1} in late night-early morning and a maximum of > 4 m s^{-1} in the late afternoon. Also, wind direction, as displayed in Figure 5, follows an accentuated daily variation with winds from the west from the early afternoon (14:00 LT), during the night and up to the early morning (7:00 LT). During the later morning (8:00 LT) and up to midday (13:00 LT) the wind direction is mainly from the east. From Figure 5 it can be concluded that the wind speed is much higher for the westerly winds in the afternoon, as compared to the easterly winds in the morning. This is consistent with the condition of the winds that operate in the foothills of the eastern slope of the western Andes mountain range, as described by López and Howell (1967). The repeated daily variations in wind speed

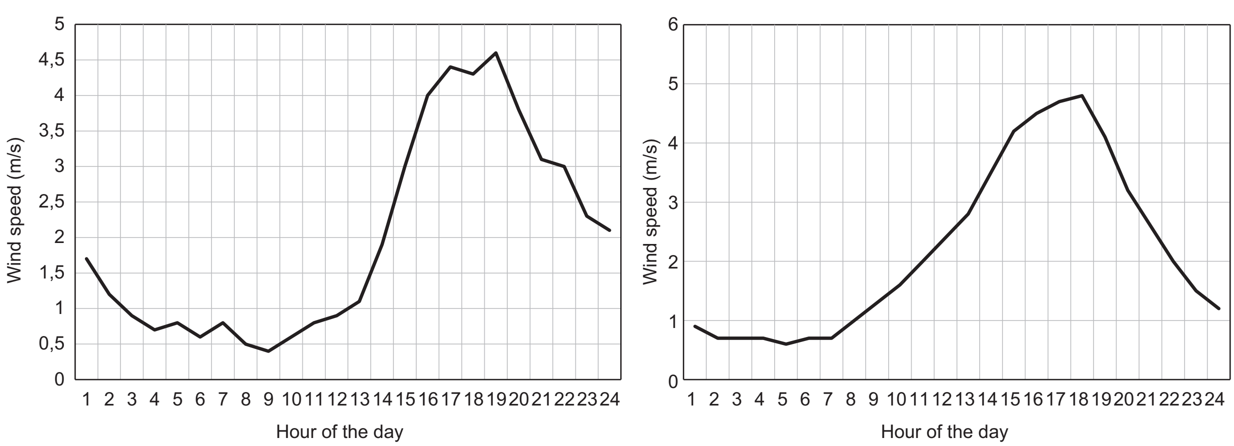

Fig. 4. Daily variation (mean values for each hour of the day on the *x*-axis) of wind speed in Vijes during the two monitoring campaigns. Left panel: January 28 to April 28, 2017 (1519 hourly data). Right panel: May 16 to October 25 (2044 hourly data).

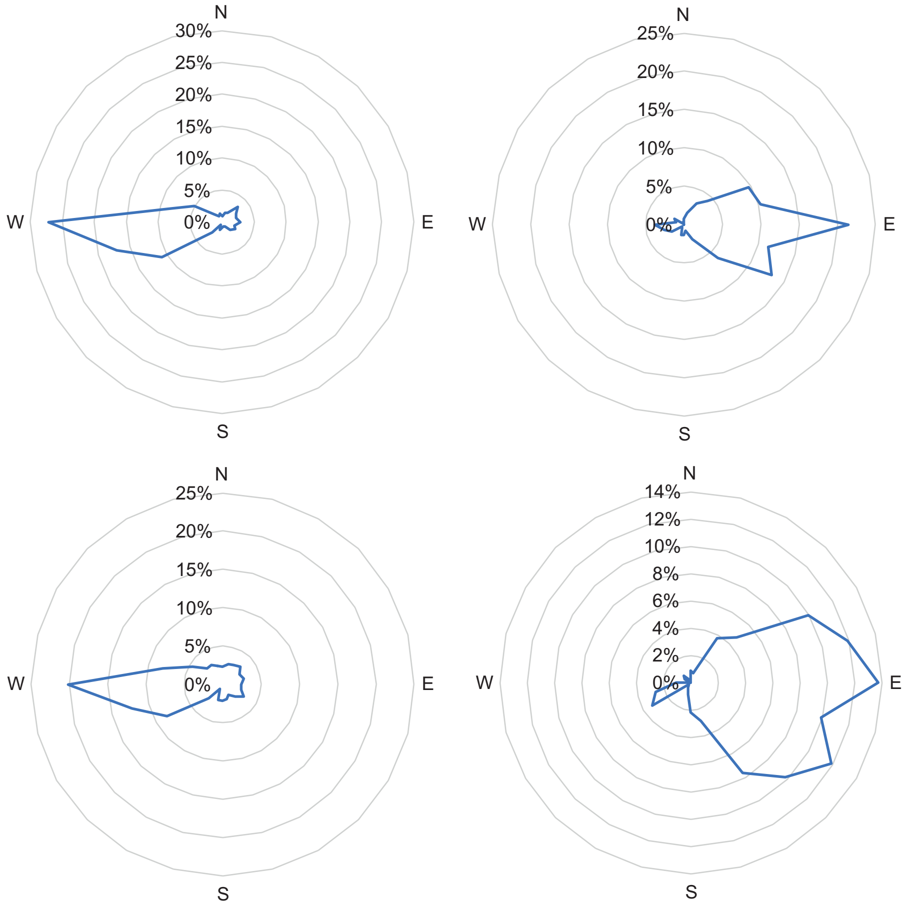

Fig. 5. Left panels: wind rose in the afternoon and night (14:00 to 7:00 LT). Right panels: wind rose during the morning until noon (8:00 to 13:00 LT). Periods: January 28 to April 28, 2017 (top) and May 16 to October 25, 2019 (bottom).

and direction have a very strong influence on how the industrial emission sources west of Vijes impact the air quality in the urbanized area.

From the analysis of meteorological data, it can be concluded that the conditions during the two campaigns were similar, with exception for more precipitation falling during the 2019 campaign.

3.3 Monitored $PM_{2.5}$ in Vijes

Table IV shows the statistics of the $PM_{2.5}$ concentrations measured during the two monitoring campaigns. Since the meteorological conditions differed in terms of precipitation between the campaigns, only the statistics for data registered during hours without rain are given. As can be seen, the registered mean $PM_{2.5}$ levels for days without rain are similar to those for the entire periods, which indicates that the difference in precipitation between periods should not be of importance while comparing the results from the two campaigns.

Data capture is highly variable between the two sensors of the 2019 campaign. The reason for this were technical problems with both sensors and their data storage.

The average $PM_{2.5}$ concentrations (13.6-18.9 µg m^{-3}) registered during the three-four months long campaigns in Vijes indicate levels below the Colombian limit value of 25 µg m^{-3}, although considerably higher than the new WHO recommended guideline of 5 µg m^{-3}. The mean $PM_{2.5}$ concentration is highest at sensor 1, located in the eastern part of Vijes.

As for the other regulated limit value (daily averaged $PM_{2.5}$ concentrations of 35 µg m^{-3}), the measurement campaigns indicate no exceedances,

Table IV. $PM_{2.5}$ concentrations measured in Vijes with sensor City center during the first campaign (January 28 to April 28, 2017), and the second campaign with sensors 1 and 3 (May 16 -October 25, 2019)*.

Sensor	All data			Only data without precipitation	
	Hourly data	Mean (SD)	Maximum (24 h)	Hourly data	Mean SD)
City center	2183 (100%)	13.6 (6.4)	25.0	1875	13.6 (6.6)
1	1592 (41%)	18.9 (5.8)	25.9	1047	18.8 (5.6)
3	3126 (80%)	17.0 (6.2)	34.0	2084	16.5 (6.5)

*Units in µg m^{-3}.

however at sensor 3 located in the western periphery of Vijes the maximum 24-h value (34 µg m^{-3}) is very close to the limit and indicate a possibility of exceedances. Another three daily averages exceeded 25 µg m^{-3}. Of special interest is to understand if the high $PM_{2.5}$ values at sensor 3 —located closest to the lime production plants— were associated to wind from the west, i.e., if their sources are industrial emissions. In order to analyze the importance of wind direction, it is necessary to consider high hourly concentrations instead of daily averages. An analysis of the events where hourly concentrations exceed 35 µg m^{-3} reveals 87 occasions, the highest hourly concentration reaching 105 µg m^{-3}. Unfortunately, the meteorological Davis station was only capturing data during 37 of those hours. The wind direction was from west during 15 occasions and from east during 22. Wind speed was low (on average 1.3 m s^{-1} [maximum/minimum of 3.5/0.1 m s^{-1}]). With westerly winds, 10 of 15 events of high hourly concentrations were registered in the night, from 23:00 to 5:00 LT. With easterly winds, 20 of 22 events took place from 8:00 to 12:00 LT. It thus appears that there are elevated concentrations around sensor 3 both with westerly winds during the night and with easterly winds during the morning until midday. Up to 6:00 LT an impact from sources different than industrial is not very likely, however afterwards other anthropogenic sources, such as traffic on partly unpaved roads, construction work or combustion of biomass within Vijes, could be expected.Thus, based only on meteorological information and the limited knowledge of potential sources of high $PM_{2.5}$ levels inside Vijes, it is not possible to determine that high hourly concentrations (which can build up to 24 h averages close to the national limit value of 35 µg m^{-3}) are a consequence of industrial emissions to the west of the city. However, it is likely that the industry —together with the heavy transport vehicles that operate to and from the lime production plants— contributes at least to portions of the high 24 h averages. An analysis of the particles' composition around sensor 3 is necessary to draw more certain conclusions on the causes of high daily averages. It should also be noted that a true evaluation of exceedances should cover at least one year of data. Considering the fairly homogeneous meteorological conditions in Vijes during the year, one could still have some confidence in that the highest 24 h averages given in Table IV may be representative, although they were measured only during parts of a year.

From Figure 6 it can be concluded that the highest measured mean concentrations, for all three sensors, are associated with winds from the eastern sector. Moreover, Figure 7 shows that $PM_{2.5}$ levels are lower during the afternoon, with winds from the west and with higher wind speeds. The highest $PM_{2.5}$ levels are typically registered in the early morning around 8:00-9:00 LT, i.e., when the wind direction normally switches from west to east and when the wind speed is at its minimum. This clearly indicates that the industrial impact from the west is not the only contributor (and most likely not the dominant one) to $PM_{2.5}$ urban background concentrations in Vijes. These results motivate a further analysis of the relative contribution of the industrial emissions to the urban background $PM_{2.5}$ levels in Vijes, using a dispersion model.

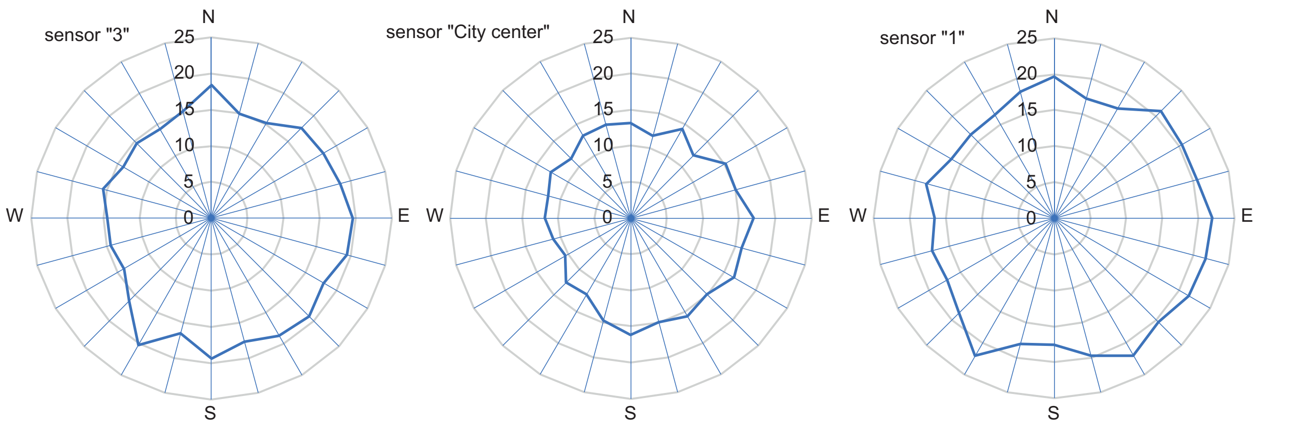

Fig. 6. Mean $PM_{2.5}$ for different wind directions during the 2017 campaign at sensor City Center (middle) and during the 2019 campaign at sensor 3 to the west of Vijes (left) and sensor 1 to the east of Vijes (right). Units: μg m^{-3}.

Fig. 7. Daily variation (mean values for different hours of the day) of monitored $PM_{2.5}$ concentrations in the Vijes urban background for all hourly data for which also meteorological data were registered (to show the same data as in Fig. 6).

3.4 Analysis of simulated and monitored $PM_{2.5}$ concentrations

Estimated emissions from all 13 lime industries are given in Table II, based on the US-EPA emission factors.

The dispersion model was run hourly for the two monitoring periods, using as input the data registered by the meteorological Davis station located in the police station tower. Figure 8 shows a comparison of the monitored daily variation of $PM_{2.5}$ together with the simulated impact of the industrial source emissions at each sensor. Some observations concerning the different contributions are shown below:

- The highest modeled impact from the industries to the west is found at sensor 3, located closest to them. Also, the City center sensor is well exposed for the industrial impact. Sensor 1 at the eastern boundary of Vijes shows, as expected, the lowest impact from industrial emissions.
- Since the simulated nighttime industrial impact (with westerly winds) at sensor 3 is considerably higher than the measured $PM_{2.5}$ concentrations, it seems highly likely that the industrial emissions, as quantified from AP-42 emission factors, were overestimated.
- The higher concentrations measured during the morning and midday observed at all three sensor locations cannot be attributed to industrial impact from the west, rather it seems that traffic and possibly other anthropogenic emissions within the city and in the Cauca River valley have dominating contributions. The contribution from traffic emissions along the national highway running east of Vijes and the rural background concentrations in the valley are transported into Vijes with easterly winds from the morning and until midday, contributing to the raised urban backgrounds during this part of the day. It is also known that biomass burning, specifically for preparing sugarcane harvests, are common in CRV and they

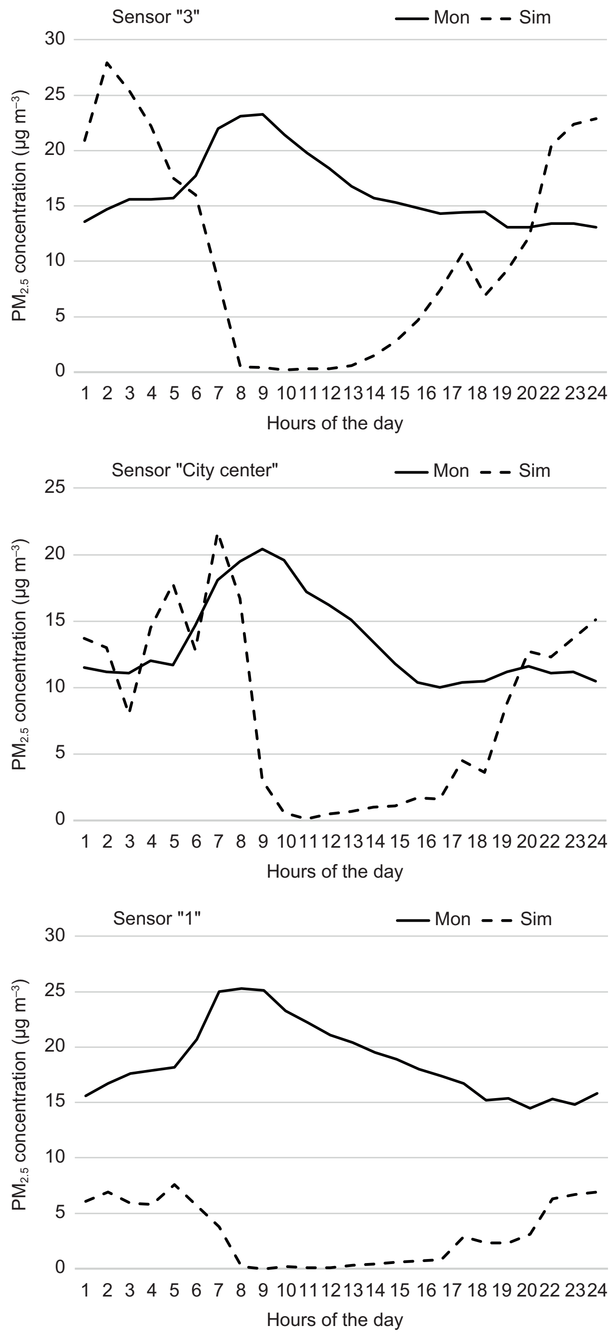

Fig. 8. Daily variation (mean values for different hours of the day) of monitored and simulated $PM_{2.5}$ contributions from the industrial emissions west of Vijes. Units: µg m^{-3}.

could add to raised particle concentrations in the air transported into Vijes.

The emission factor taken from AP-42 is an averaged factor based on a wide variety of lime production plants and should not, as also stated by US EPA, be taken as a precise estimation for an individual plant type. It can thus be relevant to assume a smaller emission factor to be valid for the Vijes lime production plants.

The air running down the mountain slope with westerly winds during the night has its origin in the rain forests between the western ridge of the Andes and the Pacific Ocean, where there are almost no anthropogenic sources of fine particles. An inspection of the lowest hourly $PM_{2.5}$ concentrations registered by sensor 3 does not give much information, since the high constant bias gives it a high detection limit. For the City center sensor, which had a bias of 4 µg m^{-3} and did not allow any registration below that value, 32 of the 35 (91%) lowest hourly $PM_{2.5}$ values in the range of 4-6 µg m^{-3} were associated with winds from the mountains in the west. The assumption that a small rural background of the order of magnitude of 1 µg m^{-3} in the air transported into Vijes with winds from the mountains to the valley, thus seems reasonable. With this clean background air, we suggest that the lime production emissions should be reduced by 40%. The assumption of this low rural background assures that the industrial impact is not underestimated. Figure 9 shows how the simulated nighttime levels at sensor 3, caused

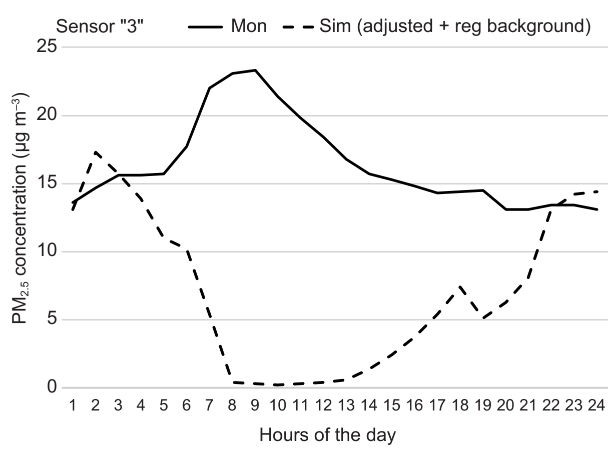

Fig. 9. Daily variation (mean values for different hours of the day) of monitored and simulated $PM_{2.5}$ concentrations summed from the industrial impact scaled by a factor of 60% plus a rural background value of 1 µg m^{-3} for all hours with a westerly wind component. Units: µg m^{-3}.

by the lime production operating continuously and a small contribution from the assumed very clean air transported down from the mountains, compare well with measured concentrations at these hours.

Based on this analysis supported by a dispersion model, the following estimations of the impact of the lime production industry in Vijes are given:

- The overall emissions as calculated based on AP-42 emission factors should be reduced by 40% from 193 t year^{-1} to 116 t year^{-1}.
- The contribution from the lime production industry to the averaged $PM_{2.5}$ urban background concentrations are:
  - Sensor 3 west of the city center: 38%
  - Sensor City center: 33%

  Sensor 1 east of the city center: 10%

4. Summary and conclusions

The two monitoring campaigns performed in the small city of Vijes, using low-cost $PM_{2.5}$ monitors calibrated against reference instruments prior to the measurement, showed that annual mean $PM_{2.5}$ concentration levels are likely to be below the Colombian limit value of 25 µg m^{-3}. As for the limit value for highest daily mean $PM_{2.5}$, the sensor closest to the lime production plants west of Vijes indicated a 24-h mean of 34 µg m^{-3}, close to the limit value of 35 µg m^{-3}. The urban background concentrations of $PM_{2.5}$ within Vijes are highly variable during the day, in response to two different wind regimes. The first, with easterly winds from the CRV, regulates the dispersion during the morning to the early afternoon of anthropogenic particles emitted by mobile and stationary sources in Vijes and from the CRV. The second with westerly winds running down the mountains, is dominating during the afternoon, evening and night, mainly transporting particles emitted by the lime production plants.

Through a description of the emissions associated with the 13 lime production units operating west of Vijes, it was possible to execute a Gaussian dispersion model and infer possible contributions from the industrial sector through a comparison with the monitored $PM_{2.5}$ levels. The results indicate that the banning of the old lime production units and the relocation of the plants located in the direct neighborhood of the Vijes residential areas, have implied a control of a possible negative and dominating impact of this industrial sector. The analyses performed indicate that today the industrial contribution to long term averages of $PM_{2.5}$ is of a maximum of 6 µg m^{-3}, i.e., a minor part of the monitored $PM_{2.5}$ levels reported of about 14 to 19 µg m^{-3}. However, an analysis based on meteorological data and a limited knowledge of emission sources inside Vijes, indicate a possible exceedance of the national limit values for maximum 24-h averages of $PM_{2.5}$ at the sensor located closest to the lime production plants. This exceedance could at least partly be built up by a short-term impact of industrial emissions and the movements of heavy-duty vehicles serving the industries.

Further studies, preferably involving an analysis of the $PM_{2.5}$ composition, are needed to better understand the local sources inside Vijes, as well as the influences from particles generated in the Cauca Valley and transported into Vijes with the easterly winds occurring early in the day. Although such details are of interest for air pollution control in the long-term run, the results indicating $PM_{2.5}$ averages ranging from 14 to 19 µg m^{-3} does not call for urgent actions.

5. Limitations

This assessment of $PM_{2.5}$ concentrations in a city without fixed air quality monitors and information on emission sources was designed to be short in time and performed with a very restricted budget for monitoring purposes. Obviously, there are several limitations following a low budget assessment like this. Some of the most important are given below:

- Low-cost optical sensors for $PM_{2.5}$ determination are normally only indicative, i.e., one could not rely on the absolute values given by the instrument. In this study an attempt was made to calibrate the instrument in an urban environment near Vijes. The intercalibration resulted in a very poor performance of one of the sensors, whose data had to be excluded from further analyses. As for the remaining three monitors, R^2 values of 0.58 to 0.73 during the calibration provided some confidence in the data registered, although two of the sensors showed large constant biases. Using a regression where the constant bias is forced to zero gave $PM_{2.5}$ averaged levels between 11.3 and 16.4, instead of the reported range from 13.9 to 18.9. The overall conclusions from this study would not change because of which regression was used, but the comparison underline the uncertainties linked to low-cost sensors output. A recommendation for future assessments with low-cost optical sensors is to perform the intercalibration both before and after the campaign; also, as recommended by Liang and Daniels (2022), during various weeks to yield better statistics.

- The sensors were located to show the urban background concentrations of $PM_{2.5}$ both in the city center and in the peripheric urban areas west and east of the city center. Unfortunately, due to limited human and economic resources, the measurements were performed as two separate campaigns during different parts of the year. However, it was possible to show that the conditions, both in terms of meteorology and monitored $PM_{2.5}$, were comparable between the two campaigns.
- A full year monitoring campaign would have given more strength to the conclusion that $PM_{2.5}$ levels in Vijes are below the Colombian limit value for the annual mean and also if the 24-h limit values close to the national limit of 35 μg m^{-3} only occur in the westernmost part of Vijes. In order to confirm the role of industrial emissions as main contributors to the short-term high $PM_{2.5}$ levels registered in the westernmost sensor 3, a filter sampling and particle composition analysis is recommended.
- The application of a dispersion model to determine contributions from the industries west of the city supported the meteorological analysis, which pointed out other major sources to $PM_{2.5}$ in Vijes and showed that the industrial impact only contributed to a minor part of the $PM_{2.5}$ averages. Instead, the dominating contribution to $PM_{2.5}$ in Vijes comes from other anthropogenic sources such as traffic, infrastructure work and biomass combustion, both inside Vijes and in the CRV. Performing a filter sampling and particle composition analysis also in the central and eastern part of Vijes would support conclusions on the magnitude of local and remote source contributions, other than those given by the local lime production plants.

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References

Airviro. 2022a. Available at: https://www.airviro.com/airviro/ (accessed on November 25, 2022).

Airviro. 2022b. Working with the dispersion module. Airviro user's reference 2: 102-105. Available at: https://www.airviro.com/airviro/extras/pdffiles/UserRef_Volume2_Dispersion_v5.00.pdf. (accessed on November 25: 2022).

Allen T. 2013. De-construction of the Shinyei PPD42NS dust sensor. EME Systems LLC. Available at: https://files.seeedstudio.com/wiki/Grove_Dust_Sensor/resource/ShinyeiPPD42NS_Deconstruction_TracyAllen.pdf (accessed on November 25, 2022).

Berkowicz R, Prahm LP. 1982. Evaluation of the profile method for estimation of surface fluxes of momentum and heat. Atmospheric Environment 16: 28092819. https://doi.org/10.1016/0004-6981(82)90032-4

Danard M. 1977. A simple model for mesoscale effects of topography on surface winds. Monthly Weather Review 105: 572-581. https://doi.org/10.1175/1520-0493(1977)105%3C0572:ASMFME%3E2.0.CO;2

Diez S, Lacy SE, Bannan TJ, Flynn M, Gardiner T, Harrison D, Marsden N, Martin NA, Read K, Edwards PM. 2022. Air pollution measurement errors: Is your data fit for purpose? Atmospheric Measurement

Techniques 15:4091-4105. https://doi.org/10.5194/amt-15-4091-2022

Fajersztajn L, Saldiva P, Pereira LA, Figueiredo-Leite V, Buehler AM. 2017. Short-term effects of fine particulate matter pollution on daily health events in Latin America: A systematic review and meta-analysis. International Journal of Public Health 62: 729-738. https://doi.org/10.1007/s00038-017-0960-y

Giordano MR, Malings C, Pandis SN, Presto AA, McNeill VF, Westervelt DM, Beekmann M, Subramanian R. 2021. From low-cost sensors to high-quality data: A summary of challenges and best practices for effectively calibrating low-cost particulate matter mass sensors. Journal of Aerosol Science 158: 105833. https://doi.org/10.1016/j.jaerosci.2021.105833

Hincapié-Aristizabel R, Delvasto-Arjona S, Contreras-Rengifo R. 2017. Los hornos de colmena de Vijes, Valle del Cauca, un patrimonio material e inmaterial que es preciso recuperar y preservar. Pontificia Universidad Javeriana – Apuntes. Revista de Estudios sobre Patrimonio Cultural 28: 24-43. Available at: https://repository.javeriana.edu.co/handle/10554/23196?locale-attribute=de

IDEAM. 2016. Informe del estado de la calidad del aire en Colombia 2011-2015. Instituto de Hidrología, Meteorología y Estudios Ambientales, Bogotá, 179 pp. Available at: http://www.ideam.gov.co/web/contaminacion-y-calidad-ambiental/informes-del-estado-de-la-calidad-del-aire-en-colombia

Jayaratne R, Liu X, Ahn KH, Asumadu-Sakyi A, Fisher G, Gao J, Mabon A, Mazaheri M, Mullins B, Nyaku M, Ristovski Z, Scorgie Y, Thai P, Dunbabin M, Morawska L. 2020. Low-cost $PM_{2.5}$ sensors: An assessment of their suitability for various applications. Aerosol and Air Quality Research 20: 520-532. https://doi.org/10.4209/aaqr.2018.10.0390

Johansson C, Olivares G, Gidhagen L. 2007. Characterization and source apportionment of particulate matter in two urban areas in Chile. Institutionen för Tillämpad Miljövetenskap, Stockholms Universitet, ITM-Report 169, 48 pp. Available at: https://www.slbanalys.se/slb/rapporter/pdf8/itm2007_169.pdf (accessed on November 25, 2022).

Liang L, Daniels J. 2022. What influences low-cost sensor data calibration? A systematic assessment of algorithms, duration, and predictor selection. Aerosol and Air Quality Research 22: 1-16. https://doi.org/10.4209/aaqr.220076

López M, Howell WE. 1967. Katabatic winds in the Equatorial Andes. Journal of the Atmospheric Sciences 24: 29-35. https://doi.org/10.1175/1520-0469(1967)024%3C0029:KWITEA%3E2.0.CO;2

Mateus-Fontecha L, Vargas-Burbano A, Jimenez R, Rojas NY, Rueda-Saa G, van Pinxteren D, van Pinxteren M, Fomba KW, Herrmann H. 2022. Understanding aerosol composition in a tropical inter-Andean valley impacted by agro-industrial and urban emissions. Atmospheric Chemistry and Physics 22: 8473-8495. https://doi.org/10.5194/acp-22-8473-2022

Morawska L, Thai PK, Liu X, Asumadu-Sakui A, Ayoko G, Bartonova A, Bedini A, Chai F, Christensen B, Dunbabin M, Gao J, Hagler GSW, Jayaratne R, Kumar P, Lau AKH, Louie PKK, Mazaheri M, Ning Z, Motta N, Mullins B, Rahman MM, Ristovski Z, Shafiel M, Tjondronegoro D, Westerdahl D, Williams R. 2018. Applications of low-cost sensing technologies for air quality monitoring and exposure assessment: How far have they gone? Environment International 116: 286-299. https://doi.org/10.1016/j.envint.2018.04.018

Nivia-Guevara A. 2001. Memoria explicativa del mapa geológico del departamento del Valle del Cauca. Escala 1.250.000. Ministerio de Minas y Energía, Instituto de Investigación e Información Geocientífica Minero-Ambiental y Nuclear, Bogotá, 148 pp. Available at: https://www.researchgate.net/publication/275971711_Mapa_Geologico_Departamento_del_Valle_del_Cauca_Escala_1250000_Memoria_Explicativa_2001 (accessed on November 25, 2022).

Rodríguez-Camargo LA, Sierra-Parada RS, Blanco-Becerra LC. 2020. Análisis espacial de las concentraciones de $PM_{2.5}$ en Bogotá según los valores de las guías de la calidad del aire de la Organización Mundial de la Salud para enfermedades cardiopulmonares, 2014-2015. Biomédica 40: 137-52. https://doi.org/10.7705/biomedica.4719

Rodríguez-Villamizar LA, Rojas-Roa NY, Blanco-Becerra LC, Herrera-Galindo VM, Fernández-Niño JA. 2018. Short-Term effects of air pollution on respiratory and circulatory morbidity in Colombia 2011-2014: A multi-city, time-series analysis. International Journal of Environmental Research and Public Health 15: 1610. https://doi.org/10.3390/ijerph15081610

US-EPA. 1998. Mineral products industry: Lime manufacturing. In: Compilation of air pollutant emissions factors (AP-42). Vol. 1: Stationary point and area sources.

5th ed. United States Environmental Protection Agency, North Caroline, USA. Available at: https://www3.epa.gov/ttnchie1/ap42/ch11/final/c11s17.pdf (accessed on November 25, 2022).

WHO. 2021. WHO global air quality guidelines: Particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. World Health Organization. Available at: https://apps.who.int/iris/handle/10665/345329 (accessed on November 25, 2022).

WMO. 2021. An update of low-cost sensors for the measurement of atmospheric composition (Peltier R E, Ed.). WMO-No. 1215. World Meteorological Organization, Geneva. Available at: https://library.wmo.int/doc_num.php?explnum_id=10620 (accessed on November 25, 2022).