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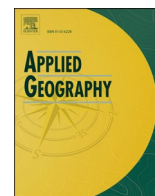
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Particulate matter pollution in an informal settlement in Nairobi: Using citizen science to make the invisible visible

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ABSTRACT

We used a citizen science approach to explore personal exposure to air pollution of selected informal settlement dwellers in Nairobi, Kenya. This paper presents the methods used, with the aim of informing others who wish to conduct similar work in the future, and some results, including policy impact. We used three interlinked methods: 1) a personal mobile exposure monitoring campaign in which individual workers used Dylus monitors to measure variations in their exposure to fine particulate matter (PM_{2.5}) within the settlement over the course of a day, 2) a questionnaire conducted before and after the monitoring campaign to assess any changes in knowledge or attitude in the wider community, and 3) two workshops, which facilitated the citizen science approach and brought together members of the community, local policy makers and researchers. The three elements of the study provided the local community, policymakers and scientists with new insights into the challenges air pollution poses for human health in such settlements, and opportunities for exploring how to monitor, mitigate and avoid these pollutants using a citizen science approach. We found significant differences in PM_{2.5} exposure between individual workers that could be partially explained by spatial differences in concentration that we identified within the settlement. Residents of the informal settlement identified a number of sources that might explain these differences in concentration, although many residents perceived air quality to be good both indoors and outdoors. The workshops raised awareness of the issue of air pollution and brought together affected community members and local and national policy makers to discuss air pollution issues in Nairobi's informal settlements. As a result, a new knowledge exchange network, the Kenya Air Quality Network, of policy-makers, researchers and community members was formed with the aim to facilitate the improvement of air quality across Kenya.

1. Introduction

Outdoor air pollution is a major environment and health issue, and a policy challenge in both developed and developing countries. The air pollutant of primary concern for human health is fine particulate matter (specifically PM_{2.5}). It has recently been estimated that PM_{2.5} and O₃ is associated with global mortality of 8.79 million people (Lelieveld et al., 2019), while Malley and colleagues (Malley et al., 2017) suggest that 3.4 million premature births globally might be associated with outdoor PM_{2.5} concentrations. An estimated 90% of the world's population is breathing air which exceeds WHO Air Quality Guidelines for PM_{2.5} (WHO, 2016a). In low and middle income countries, 98% of cities do not

meet these guidelines, whilst in high income countries this falls to 56% (WHO, 2016b), but most monitoring of PM_{2.5} takes place in high income countries, rather than the low and middle income countries where the problem is worse (Lelieveld et al., 2019). This mismatch between the severity of pollution problem and the degree of monitoring is particularly marked in Africa (UNEP, 2016, p. 215); the WHO Ambient Air Pollution database only contains data from 39 locations throughout Africa, of which 37 exceed the WHO annual mean guideline, the two exceptions being located in rural Liberia (WHO, 2016b).

There are few measurements of air pollution exposure in the different communities of African cities, where large numbers of people live in informal settlements (in 2012, 61.7% of urban population in Sub-

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Saharan Africa (UN-Habitat, 2013, p. 2077)). Given the close vicinity of these informal settlements to industrial plants, dump sites and dirt tracks, and the intensive use of biomass fuels within them, these residents may be exposed to a very different mix of pollutants to those measured by the regulatory monitoring stations, which provide data to the WHO Ambient Air Pollution database and typically measure urban background concentrations in more affluent areas of cities. Few studies have addressed this major issue of social equity, although research in Accra indicates its potential importance (e.g. (Rooney et al., 2012a)). Here, outdoor PM_{2.5} concentrations were twice as high in low- than in high-income communities, with pollution hotspots being associated with local activities such as waste burning, use of wood stoves, fish smoking and loose dirt roads. This demonstrates not only the larger potential benefits of emission control in more impoverished communities, but also that different sources contribute to their higher exposure. Higher exposure of poorer communities has also been reported in Ho Chi Minh City (Mehta et al., 2014), and in Europe and North America, economically deprived people have higher rates of mortality related to outdoor air pollution (Deguen & Zmirou-Navier, 2010; Finkelstein, Jerrett, & Sears, 2005; Laurent, Bard, Filleul, & Segala, 2007). Indoor exposure to air pollutants may also be greater in informal settlements, because of greater penetration of outdoor pollution due to the materials typically used for building the homes (see (Wekesa, Steyn, & Otieno, 2011)), use of polluting fuels for cooking and heating, and inadequate ventilation (Adamkiewicz et al., 2011). Furthermore, people in these informal settlements often have fewer opportunities to escape from the high levels of air pollution to which they are exposed to, due to high unemployment levels and irregular incomes (Wekesa et al., 2011). Citizen science approaches can be used to help explore the pollutants residents are exposed to on a daily basis and fill in the gaps in air pollution measurements. This is possible due to the rapid development of low-cost sensors for air pollution.

Nairobi has a population of 3.1 million (2009) of whom an estimated 60% live in around 200 informal settlements (CURI, University of Nairobi/Muunagano wa Wanavijiji, 2014). The densely populated informal settlements often occupy marginal lands, including areas near to large roads and industrial facilities (Egondi et al., 2013). PM_{2.5} concentrations in Nairobi have been measured routinely since 2008 until recently at two rooftop urban background sites, where Gaita and colleagues (Gaita, Boman, Gatari, Pettersson, & Janhäll, 2014) reported a mean concentration of 21 $\mu\text{g m}^{-3}$ over two years, with the biggest contribution being from mineral dust and traffic. However, the actual exposures experienced by inhabitants may greatly exceed these rooftop concentrations. For example, Kinney and colleagues (Kinney et al., 2011) report an intensive campaign over two weeks in July 2009 in which weekday daytime concentrations at three roadside locations, including within the central business district of Nairobi, ranged from 75 to 100 $\mu\text{g m}^{-3}$, exceeding those at the urban background site by a factor of 3–4. In a second pilot study in August 2011 (Ngo, Kokoyo, & Klopp, 2017), three individuals from four groups representing high occupational exposure, including women in an informal settlement, recorded mean daytime exposures to PM_{2.5} between 57 and 103 $\mu\text{g m}^{-3}$, consistent with the exposures recorded by Kinney and colleagues (Kinney et al., 2011). More recently, deSouza and colleagues (deSouza et al., 2017) reported PM_{2.5} concentrations at schools in two informal settlements that were approximately twice those in a wealthy part of the city. High indoor exposures to PM_{2.5} have also been reported inside homes in informal settlements in Nairobi, especially those cooking with biomass fuels (Muindi, Murage, Egondi, Rocklov, & Ng, 2016).

There is evidence that some residents living within some informal settlements in Nairobi are aware of the problem of air pollution within their community. Egondi and colleagues (Egondi et al., 2013) developed a map of perceived air quality within two informal settlements (Viwandani and Korogocho) based on over 5000 questionnaire responses, although this did not include any direct measurement of pollutant concentrations. A subsequent study in the same two informal

settlements (Muindi, Egondi, Murage, Rocklov, & Ng, 2014) used focus groups to explore inhabitants' perceptions of the issues in more detail; they found that, although residents identified industries and dumpsites as major sources of outdoor pollution, they took few actions to reduce their exposure and showed a lack of agency to address these problems. Therefore, new approaches are needed to engage residents with the issues of air pollution. One way to do this is through actively engaging people in monitoring their own exposure to air pollution.

The rise of 'citizen science' approaches in the last few decades (Bonney et al., 2014), linked to the development of a new generation of personal monitors providing continuous records of personal exposure (e.g. (Jovašević-Stojanović et al., 2015; Steinle et al., 2015)), offers new opportunities to actively engage communities with the highest health burdens from air pollution in monitoring their local environment and identifying measures that might reduce their exposure. The need for community-based research into exposure has been highlighted, as it has the potential to stimulate local action (Adamkiewicz et al., 2011; Commodore, Wilson, Muhammad, Svendsen, & Pearce, 2017; Hsu et al., 2017), if specifically designed to do so (see (Bonney, Phillips, Ballard, & Enck, 2016) for a discussion of this), via increased awareness of an issue combined with self-efficacy (belief that oneself can affect change, see (Kollmuss & Agyeman, 2002)). An early example of citizen air quality monitoring leading to action is the Bucket Brigade, where low-cost sensors were used by various communities across the USA to demonstrate the need for increased monitoring of air quality around specific sites, push for new policies to protect health, and lead to increased awareness in the communities about air quality (O'Rourke & Macey, 2003).

However, raising awareness can also reduce feelings of empowerment if it is felt that risk is transferred from the polluters to those directly affected by the pollution (Hubbell et al., 2018). Community-led citizen science also has the potential to contribute to policy assessment and implementation within city government (Van Brussel & Huyse, 2018), provided appropriate political linkages are established.

This paper describes what we believe is the first study in a major African city to actively engage the community of an informal settlement in monitoring and mapping the air pollution within it, linking this directly to their perception of issues, and to the air pollution policy framework in Nairobi. Our main research question was: 'Can citizen science approaches quantify individual exposure to air pollution, whilst raising awareness of the issue amongst community members and policy-makers'. In the interests of developing similar work in the future, we discuss the limitations of our study and make recommendations based on these.

The work was carried out within one informal settlement in Nairobi, with PM_{2.5} measurements made in September and October 2015, at the end of the cool dry season when concentrations are relatively high (Gaita et al., 2014). Ethical approval for the work was granted by the University of York Environment Department Ethics Committee.

2. Methods

2.1. Approach

Citizen science is the partnering of scientists and non-scientists to work together to answer scientific questions (Dickinson et al., 2012). In Bonney and colleagues' typology of citizen science (Bonney et al., 2009), our study was a collaborative project, in which study participants and stakeholders were engaged in planning, design and implementation. This approach can allow incorporation of local knowledge into the scientific process (Cigliano et al., 2015; Ramirez-Andreotta, Brusseau, Artiola, Maier, & Gandolfi, 2015) and ensure that research is focused on issues of concern to local residents. There were three interlinked elements to the research: particulate matter monitoring, a questionnaire (conducted before and after the monitoring campaign in order to assess any changes in knowledge during the campaign) and two workshops.

The workshops were attended by community participants, other community stakeholders and local and national policy-makers to discuss priorities for air quality management in the city. The first workshop raised awareness about air pollution and its' health effects and gave the opportunity for local residents and policy-makers to input into study design, including monitoring routes and where to administer the questionnaire. The second workshop provided time for discussion of the results and consideration of potential actions which could be taken by local and national government representatives and local citizens. As such, both workshops formed an integral part of the citizen science approach.

2.2. Study site

The study was carried out in Mukuru, as we were approached by Muungano Wa Wanavijiji (MWW) (affiliated to Slum Dwellers International), an organisation with a long history of working in the area, who had received multiple complaints from residents about air pollution, and MWW wanted monitoring to take place. Mukuru, like many other similar informal settlements in East Africa, has mainly developed as a result of people moving for economic reasons from rural to urban areas. Mukuru is sandwiched within Kenya's largest industrial hub located to the east and southeast of Nairobi. The hub is dominated by small- and medium-sized industries, which include food processing, power generation, chemical processing, battery manufacturing, plastic production and scrap metal recycling (see (Egondi et al., 2013)). Residents live in semi-permanent rented structures made of tin, which are characterised by poor ventilation due to small or no windows as a result of security concerns. They have improvised ceiling insulation to minimise the effect of low temperatures during the cold season. Conditions are cramped, with huts constructed back-to-back. Our focus was on two settlements within Mukuru: Mukuru Kwa Reuben and Viwandani (see Fig. 1), which cover 151 ha and were home to 168,651 people in 2016 (UC Berkeley et al., 2017). Temperature varied during the monitoring period from 13 to 29 °C, with a mean air humidity of around 60%. Wind speeds were generally low (under 15mph) and were predominantly from the east or northeast (from timeanddate.com).

2.2.1. Monitoring methods

Three battery-powered low-cost particle counters (Dylos 1700; Dylos Corporation, Riverside, California, USA) were used for the personal monitoring campaigns. These mobile monitoring devices use a light-scattering technology, have been tested both indoor and outdoor by scientists and community members (Semple et al., 2012, 2015) and perform well when compared with other established methods for measurement of PM concentrations (Holstius, Pillarisetti, Smith, & Seto, 2014; Northcross et al., 2013; Steinle et al., 2015). A calibration of these mobile devices through co-location with a high-precision stationary PM measuring device is important (and was carried out in this study, see below), as is the cross-calibration of all used mobile devices in a campaign. During the personal monitoring campaigns, alongside each Dylos was a GPS Trackstick (Telespial Systems Inc, California, USA), a lightweight (82g) device which every 10 s records date, time, latitude and longitude, altitude, speed, direction and temperature. More details on the Dylos sensors and Trackstick can be found in (Steinle et al., 2015). For the measuring campaigns, the Dylos were deployed in small rucksacks which – in combination with the GPS – were carried around by the community members while following their daily routine. An important feature of this study was that community members themselves chose where to monitor, rather than walking routes prescribed by the researchers, so the monitoring reflects levels of PM_{2.5} actually experienced by community members on a daily basis.

In order to convert the Dylos particle number concentrations to PM_{2.5} mass concentrations and to cross-calibrate the Dylos sensors, the three sensors were run, for a period of 3 days (23rd-25th October 2015), alongside a Mobile Air Pollution Laboratory owned by the Kenya Meteorological Department, which functions as a regulatory monitor and uses a GRIMM Aerosol Technik Environmental Dust Monitor model 180. The relationship between the two monitoring methods was given by the following equation: PM_{2.5} mass concentration ($\mu\text{g m}^{-3}$) = 0.00004271 x Dylos number concentration (particles ft^{-3}) ($r = 0.26$). Whilst this r value is low, the Dylos PM readings generally followed the trends recorded by the regulatory monitor and were therefore considered sufficiently calibrated. The conversion factor for the three Dylos monitors differed by less than 10%, indicating that measurements made



Fig. 1. Location of the study area within Kenya, Nairobi and the immediate neighbourhood. Note the industries surrounding the informal settlements, which are served by railway lines and a network of roads. Basemap is Google Earth, settlement outlines added via MyMaps using data provided by Muungano Wa Wanavijiji (2015). The inset map of Nairobi County is by Omondi (from Wikimedia Commons), the blue box shows the extent of the Google Earth map. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

by different Dylos instruments could be readily compared.

2.2.2. Participant recruitment

Six community champions were selected to carry the monitors. MWW selected champions who were settlement residents and who had a variety of occupations, in order to sample a range of places and jobs within the informal settlement. They consisted of a roadside vendor (female), a door to door grocer (male), a second-hand clothes hawker (female), two people involved in community development work (female), and a young person involved in a community clean-up campaign (male). As for most residents of the area, the champions' indoor living environment consisted of a single room which serves as a sleeping, sitting and cooking area. The community champions were trained how to handle the equipment used in the study and given a one page set of instructions on how to operate it. Two sets of three champions (four from the area of Mukuru kwa Rueben and two from Viwandani) carried the monitors for up to two weeks, depending on their availability and other commitments, whilst moving around during their daily activities. The champions chose their own sampling routes, consistent with their daily activities, helping to ensure that the monitoring represented typical exposures of settlement residents. The champions were asked to monitor a morning and evening assessment cycle, allowing time to charge the monitors in between the two cycles. The target was to record at least 5 h of data in the morning cycle and at least 3 h in the evening cycle making a total of up to 8 h per day. Alongside a GPS tracker, champions were asked to keep a handwritten activity log detailing where they were in the settlement every few hours, and whether they were indoors or outdoors. Every 2–3 days the champions met the fieldwork project coordinator to download the data onto a PC. Assessments began in September when the weather condition in Nairobi was mainly sunny and dry, and was stopped with the onset of the short rainy season around mid-October 2015. After the monitoring campaign finished, three community champions walked around the settlement with a GPS tracker noting the locations of potential sources of pollution.

2.2.3. Questionnaire

A structured questionnaire was designed (see Supporting Information Table S2) and conducted face-to-face with a convenience sample of members of the local community, with a non-representative mix of ages (between 18 and 55) and genders. Oral consent was obtained as our experiences working in the settlement previously indicated that written consent would place too large a barrier to participation. Respondents included street vendors, restaurant owners, shop owners, carpenters, factory workers and housewives. The perception surveys were conducted by six research assistants recruited by MWW from the local community, each of whom was paired with an experienced researcher. These research assistants had experience of working with MWW, had previously conducted surveys in the community, and were trusted in the area. The research assistants were trained how to administer the questionnaire.

Before administering the questionnaire, informed consent was obtained by explaining to the participants what the objectives of the study were. Questionnaires were conducted in Swahili, English or Sheng (a mixed language commonly used amongst poorer people in Nairobi), and responses written down by the research assistants. The questionnaire was composed of 13 questions, focusing on people's perception of air quality in their area (indoor and outdoor), knowledge of the sources of air pollution, where they had previously heard about air pollution, and whether they thought they can influence their exposure to pollution. Sources of air pollution for this questionnaire were based on a questionnaire developed by Kanyiva Muindi (see (Muindi et al., 2014)) and modified after discussion in the initial workshop. The survey was conducted first in September 2015 at the beginning of the project and then repeated in November 2015, in order to assess any changes in perception throughout the project.

During the first phase of the survey, 193 respondents completed the

questionnaire, of whom 100 were male and 93 were female. The repeat survey then targeted the same respondents ($n = 136$, 67 male, 69 female). However, due to the transient nature of home rental and economic activities in the settlement, some respondents could not be located a second time.

2.2.4. Workshops

A project inception workshop was held on September 15, 2015 with 40 stakeholders from the local community, local administrators and national and county government officers, researchers, individuals from civil society organisations and our research assistants and community champions. The aim was twofold: to raise awareness of the project, and to gain feedback from stakeholders on the study design. Mechanisms for collaboration among different stakeholders and a common understanding of the study approach and objectives were developed.

An end of project workshop was held on 5th December 2015, with 47 participants who included community representatives from the informal settlements, officers from government agencies (the National Environment Management Authority, National Council for Science and Technological Innovations and Kenya Meteorological Department), representatives from UN agencies (UN Environment Programme and UN Habitat), researchers and academics from Kenya (University of Nairobi and Africa Population and Health Research Center) and abroad (Stockholm Environment Institute (SEI) York, University of Gothenburg, UC Berkeley), a representative from Media for Environment, Science, Health and Agriculture (MESHA) and medical experts from the Nairobi County Government. The workshop was designed to encourage the sharing of knowledge and experiences between different actors, and specifically to increase understanding among experts and environmental agencies of studies and initiatives that had been undertaken in Nairobi on air quality. Another important function of the workshop was to provide a forum for community members, scientists and policy-makers to discuss the findings, interpret the data, and to give people a better understanding of the experiences of those living in the settlement. Providing such spaces for discussion is one way of blurring boundaries between 'expert' and 'lay' knowledge and giving an opportunity for science to meet the public (Nowotny, 1993). The workshop had two specific objectives: to identify actions for stakeholders on data collection and research, policy formulation and implementation, and education, information and public awareness; and to find a mechanism for ongoing collaboration to achieve these actions.

2.2.5. Data analysis

Descriptive statistics were based on the downloaded 1 min average data, although values were not available for every 1 min period. Data were coded as "indoor" if the time period in which they were recorded fell within an indoor activity defined in the participant activity log and the GPS data logged no or very reduced movement. Unfortunately, one of the GPS trackers was lost during the course of the campaign, so that not all measurements could be reliably assigned to an indoor or outdoor location. For this reason, data from a community development worker (champion 5) and a roadside vendor (champion 6) could not be used in comparisons of indoor and outdoor concentrations or in model fitting.

Statistical analysis of PM_{2.5} exposure data was carried out using the R analytical software (build 3.2.2), and the "MASS" package. The geometric mean PM_{2.5} concentration for each 30 min period was used as the response variable; note that the number of 1 min values used to derive these values did vary. Generalised linear models (GLM) with a Gaussian link were used to identify the factors related to PM_{2.5} exposure. The analysis of these fitted models aimed to identify any significant differences between the exposure of individual champions, between indoors and outdoors, and between date and time of day. The Dylos monitor number was also included, to check for any significant deviation between monitors, but was never a significant term in the models. The analysis was carried out for the whole data set as well as using outdoor coded data only.

3. Findings

3.1. Personal monitoring results

As Table 1 shows, 1 min average PM_{2.5} concentrations ranged from around 6 $\mu\text{g m}^{-3}$ to over 300 $\mu\text{g m}^{-3}$. The highest recorded 1 min average concentration (346 $\mu\text{g m}^{-3}$) was recorded by one of the community development workers, although due to a lost GPS we do not know where this occurred. Mean values for each person were between 22.4 $\mu\text{g m}^{-3}$ and 39.6 $\mu\text{g m}^{-3}$, with all champions experiencing large ranges in PM_{2.5} exposure through time. The door-to-door grocer and street vendor (champions 4 and 6) had a higher mean exposure than the other four participants.

Fig. 2 provides a comparison of 1 min average PM_{2.5} concentrations for the four community champions for whom indoor and outdoor locations can be reliably assigned. No indoor time was identified for champion 3. For the other three champions, the median concentration was higher indoors than outdoors. In contrast, the highest 1 min average concentrations were reported outdoors, and there was a greater scatter in the outdoor data; however, more measurements were made outdoors than indoors, and hence there was a greater chance of an isolated high reading.

Details of the fitted models from the GLM analysis are provided in Supporting Information (Table S1). The first fitted model, including all data and all factors, identified only date and time of day as significant factors; there was no significant effect of location (indoors/outdoors) and no significant difference between champions. As shown in Fig. 3, PM_{2.5} exposures were higher in the evening; the mean concentrations between 19.00 and 21.00 were significantly higher than at other times of the day. Fig. 3 also shows that concentrations were higher during the morning than the middle of the day; however, there were fewer observations made by the champions in this morning period and this effect was not statistically significant.

When the model was run for outdoor data only (and hence indoor/outdoor location was not a factor), date and time remained significant factors, and there remained no significant difference between champions (Table S1, Model 3). As with the whole dataset, concentrations were elevated in the evening, with a significant effect between 19.00 and 20.00 (see graph in S3). The date effect was also similar to that for the whole dataset, with elevated concentrations of 23rd and 24th September, and lower concentrations on 28th September; there were also significantly elevated concentrations on 7th October.

The champions tended to spend most time indoors at the end of their working day. Therefore, the time of day effect identified in the model for the full dataset may be due to champions being more likely to be indoors. The full dataset model was thus re-run excluding time of day as a factor (Table S1, Model 2). This model showed significantly greater mean PM_{2.5} concentrations indoors than outdoors ($t = -2.909$, $p = 0.00396$), with a difference of 12.3 $\mu\text{g m}^{-3}$. This model, like the others, showed a significant effect of date, but the dates observed differed from the full data model. Unlike the other models, there was also a significant difference in concentrations between the participants. The lowest

concentration was recorded by champion 3, with the mean concentration recorded by champion 4 being 10.1 $\mu\text{g m}^{-3}$ higher than that for champion 3, a difference which is almost identical with the descriptive statistics in Table 1. However, in the fitted model, champion 2 was estimated to have a mean concentration 13 $\mu\text{g m}^{-3}$ higher than champion 3, a much greater effect than shown by the raw data (data not shown).

Fig. 4 shows the spatial variation in all the 1 min average PM_{2.5} concentrations measured by the four champions with functional GPS during the monitoring campaign. The map reveals that champions 1 and 3, who experienced lower mean exposures, tended to use different areas of the settlement than champions 2 and 4, who tended to focus their time further south, in Kwa Rueben. Fig. 4 also shows locations of possible sources of pollution identified by members of the community. While this does not allow us to assign exposure to specific sources, it does indicate that champion 3, with the lowest exposure, spent more time in areas with few identified sources, while there was a high number of potential sources in the areas used by champions 2 and 4.

In order better to display the spatial variation in PM_{2.5} exposure, Fig. 5 shows the mean concentration in each 50 × 50 m grid square, using data for all four champions within that grid square. This shows a more consistent spatial pattern than is apparent in Fig. 4. There are areas of the settlement, mainly frequented by champions 1 and 3, which have mean concentrations below 25 $\mu\text{g m}^{-3}$. In contrast, mean concentrations above 100 $\mu\text{g m}^{-3}$ were concentrated in the south of settlement, an area which was mainly frequented by champions 2 and 4. This coincides with the location of manufacturing, cleaning and recycling industries, as shown in Fig. 4. In addition to the potential point sources of PM_{2.5} reported by community champions, there are many additional factories within the settlement, although it is difficult to assess their impact as the factory owners and workers are hostile to people who try to get too close to the factories to take pictures or ask questions. Such factories may also account for the high concentrations in other locations, for example, the high readings in the west in Fig. 5. Wind direction and speed are important for determining where personal exposure to the pollutants from these sources are highest, but these were not monitored during this study and would require sophisticated modelling, as often particles are detected some distance away from their source.

3.2. Perceptions of air quality

Respondents were asked to list three things that came to mind when they heard the word pollution, in order to give an indication of how people perceive pollution and whether air pollution features in their perceptions. Two-thirds of respondents mentioned air pollution of some kind; this stayed consistent between the surveys (66% in the first survey and 64% in the repeat). The responses are shown in Table 2. This highlights that although air pollution and industries feature quite heavily in responses, drainage, garbage and waste were also mentioned frequently, with drainage being the most frequently mentioned word.

Although drainage channels are perhaps not an obvious source of air pollution, in this settlement they may be. They often contain bags of

Table 1

Descriptive statistics of PM_{2.5} personal exposure ($\mu\text{g m}^{-3}$) for each champion, based on 1 min average values of all data, both indoors and outdoors. N is the number of recordings.

Community champion (M = male, F = female)	Dates	All records			Outdoor records			Indoor records		
		N	Geometric Mean	Range	N	Geometric Mean	Range	N	Geometric Mean	Range
1: Clothes Hawker (M)	19–30 Sept	603	24.8	6.2–200.9	531	23.4	6.2–200.9	72	38.6	23.4–82.6
2: Community development worker (F)	16–29 Sept	491	27.0	6.4–228.2	457	25.8	6.4–228.2	34	49.4	23.0–94.8
3: Youth activist (M)	10–13 Oct	715	22.4	5.3–97.9	715	22.4	5.3–97.9	0	–	–
4: Grocer (M)	2–12 Oct	976	32.5	6.6–150.8	922	32.3	6.6–150.8	54	35.6	15.8–97.5
5: Development worker (F)	17–24 Sept	988	25.1	8.9–346.5	–	–	–	–	–	–
6: Vendor (F)	25 Sept–13 Oct	759	39.6	7.3–250.2	–	–	–	–	–	–

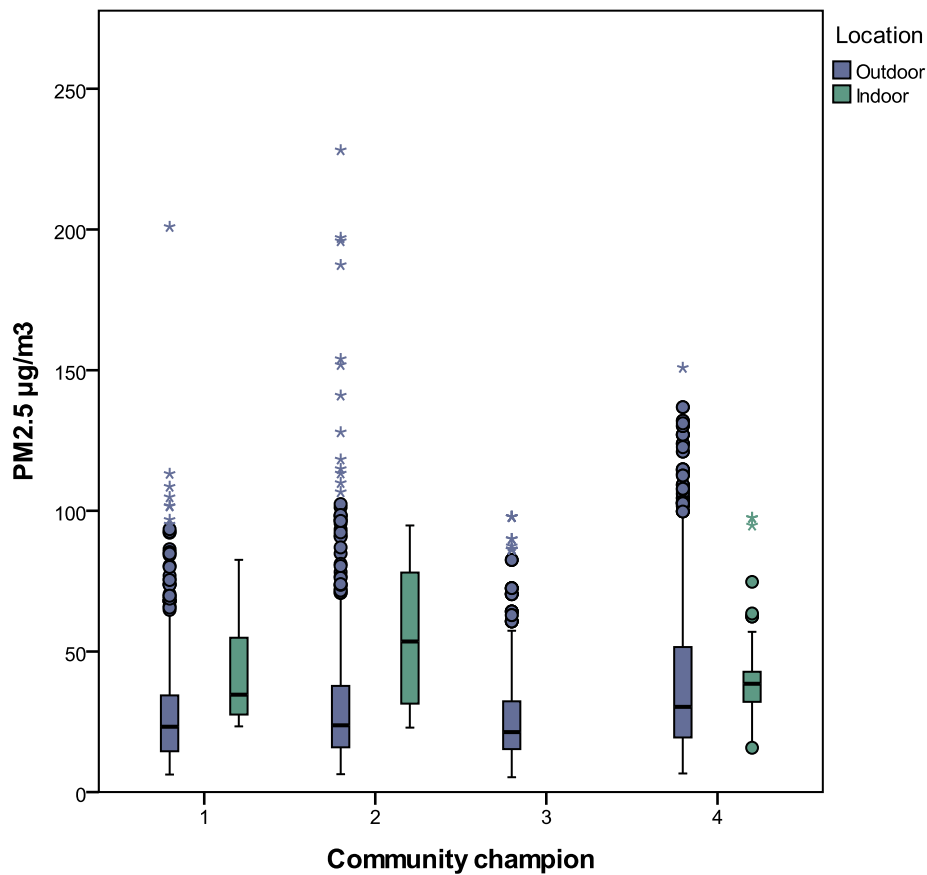


Fig. 2. Values of indoor and outdoor personal exposure to PM_{2.5} (µg m⁻³) for the whole monitoring period with bars showing the 25th and 75th percentiles, the horizontal line showing the median value, the circles showing the outliers, and the stars indicating extreme outliers. Note that these data exclude the community champions (5 and 6) for whom the GPS tracker was lost.

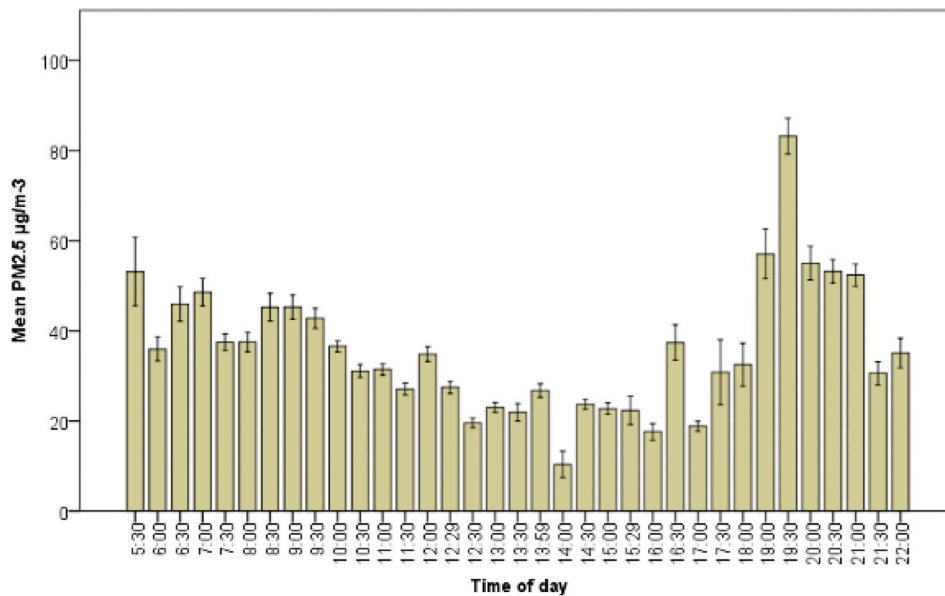


Fig. 3. Variation in mean personal exposure to PM_{2.5} (µg m⁻³) with time of day. The plotted values are the mean of all recorded values, from all champions and dates, in that half-hour period, with error bars representing ± 1 SE.

human faeces ('flying toilets'), decomposing organic waste and urine which are likely to be a source of ammonia. The prevalence of responses relating to rubbish perhaps indicate that respondents do not see air

pollution as distinct from any other pollution, or that these other forms of pollution are perceived as being more pressing and visible concerns in the settlement. This is supported by responses to the question about

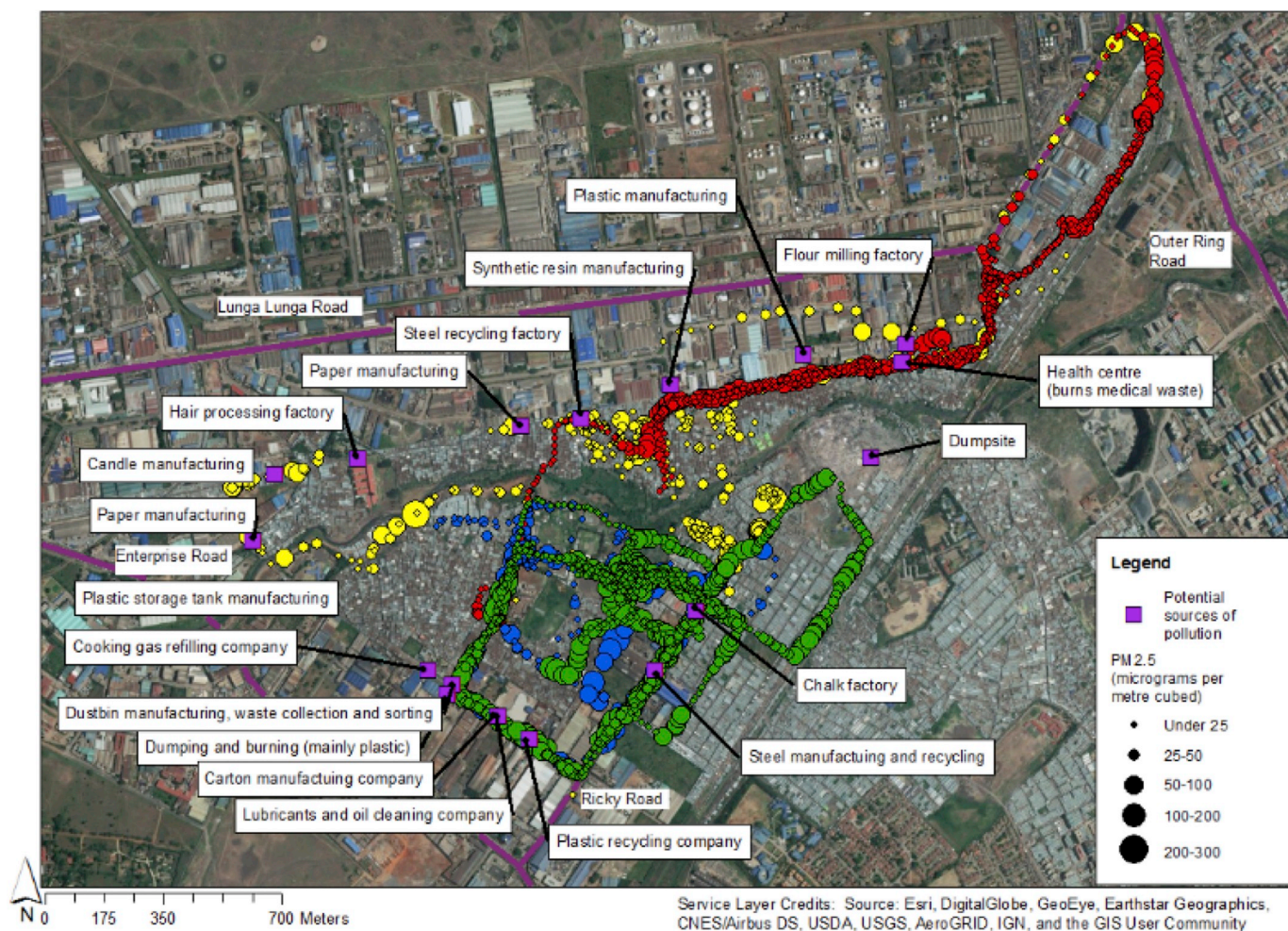


Fig. 4. 1 min average $PM_{2.5}$ concentrations ($\mu g m^{-3}$) recorded by participants over the whole of the monitoring period indicated in Table 1 plotted against the location in the settlement indicated by the GPS tracker. The data are coloured as follows: yellow = clothes hawker (community champion 1), blue = community development worker (community champion 2), red = youth activist (community champion 3) and green = grocer (community champion 4). Also shown (in purple) are potential sources of pollution as identified by community members. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

what they could do about air pollution: “I can, through my own actions, strongly influence my exposure to air pollutants”, where the most common actions given by respondents were relating to improving methods of disposing litter (26% of respondents), for example “Remove litter near my house”, improving drainage and keeping the environment clean.

Residents were asked what they thought the air quality was like indoors and outdoors in the settlement. In contrast to the data from the mobile PM sensors, residents’ perceptions were that air quality was worse outdoors than indoors, with 67% indicating indoor air quality was either ‘very good’, ‘good’ or ‘neither good nor bad’, compared to 35% rating outdoor air quality in the same way. Respondents were asked to elaborate on their answers. Responses from those who thought outdoor air quality was good/neutral included “Because people still survive and they have never fallen sick”, and “The quality of air fluctuates, sometimes you feel the air is clean and then it gets bad”. Typical responses from those who felt indoor air quality was good were “I maintain tidiness in my house” and “using a fan and gas cooker”. The people who felt that indoor air quality was very poor tended to mention sources of pollution outside the home e.g. “sewer next to my house”. Respondents were also asked to name the sources of pollution in their home. As shown in Table 3, stoves were most commonly mentioned, but drainage was also a popular response, and there were some less obvious sources mentioned including “dirty utensils”, “untidiness in the house” and “dead rats”.

3.3. Knowledge and awareness changes

Our questionnaire found limited evidence of change in people’s knowledge about air pollution over the duration of the project, as there was no change in the percentage of people naming different sources of air pollution, and no change in how polluted they thought the air was (either indoor or outdoor). However, quotes from two of the MWW research assistants suggest some change in knowledge:

“I sometimes travel upcountry for two days or so, but when I get back, I always start sneezing. I used to think it was normal because of travelling until Stockholm Environment Institute came to Mukuru last year to research on air pollution. That is when I learnt that the sneezing was not normal.” (Doris)

“I had a good experience being part of the research because I also got to learn about air pollution and that stopping it can only start with us before we approach other players like factories and other stakeholders.” (Elizabeth)

In addition, a greater proportion of people had heard about air pollution in the preceding months in the repeat questionnaire. In the first survey, 38% of respondents had heard something about air pollution in the preceding six months, whilst in the second survey this had risen to 48%. In the first survey, radio and TV were the most common

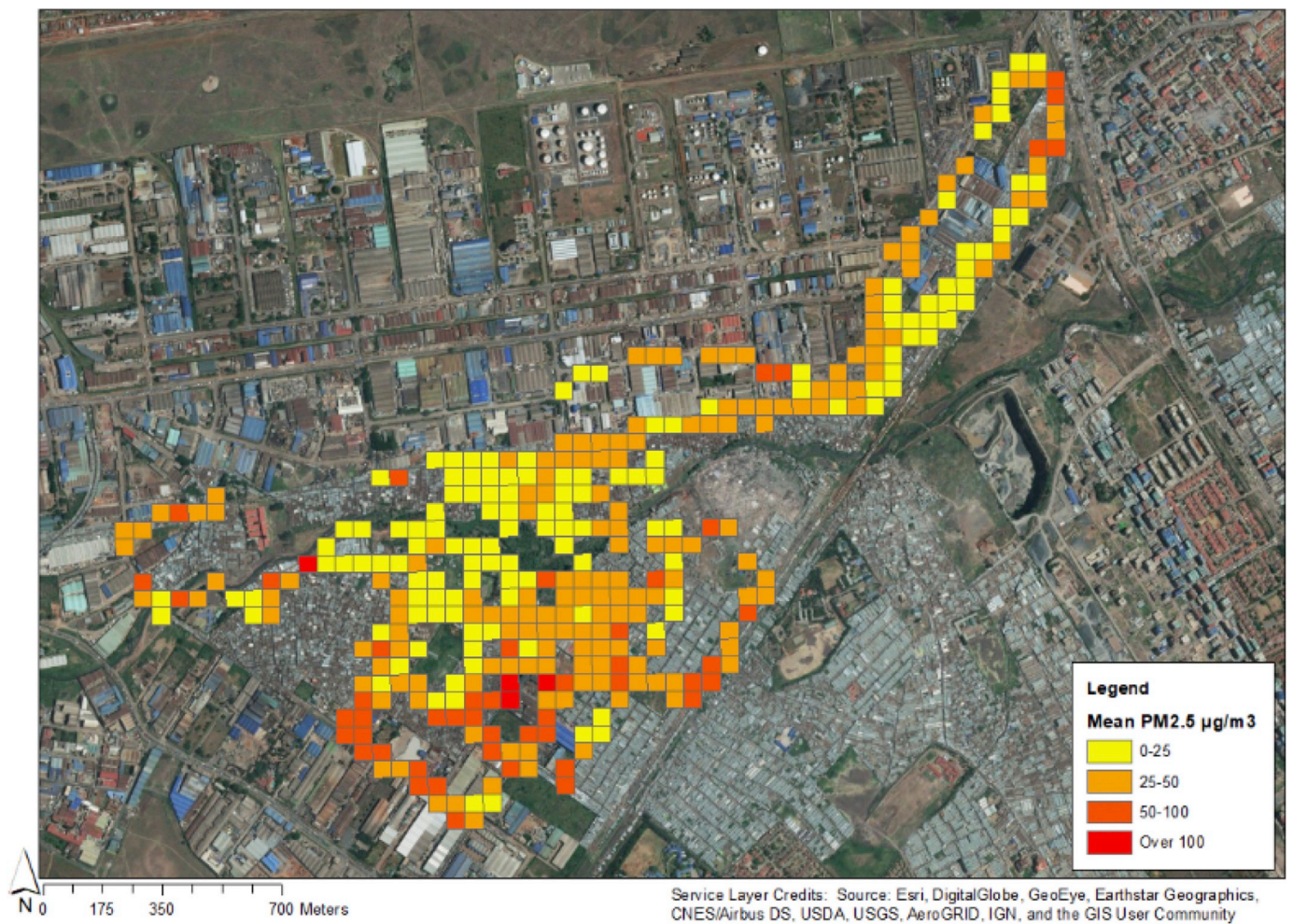


Fig. 5. Mean of 1 min average $PM_{2.5}$ concentrations ($\mu g m^{-3}$) in each 50 m grid square of the settlement, based on all the data recorded by the four participants over the whole of the monitoring period indicated in Table 1 in that grid square.

sources of information, whilst in the repeat questionnaire, ‘Other’ was the most common response (27% respondents), with informal discussions and SEI (the project lead) & MWW frequently mentioned. This is important, because increased awareness can be a precursor to behaviour change and action, although this is by no means a straightforward relationship (see (Kollmuss & Agyeman, 2002)).

The final workshop presented the findings of the study and gave a rare opportunity for policy-makers and other decision-makers to engage with community members about air pollution. Most of those attending the workshop had never met with members of the other groups before. There was intense debate, which highlighted the challenges and hurdles faced by both community members and policy-makers. Government officials learned about the day-to-day actual and perceived effects of air pollution on informal settlement residents (as well as all other hurdles these residents have to face), while informal settlement residents learned from the government officials about the complex task of developing, ratifying and implementing measures that reduce environmental impacts while at the same time securing sustainable development including job opportunities and economic prosperity. This debate concluded that a more formal structure facilitating the improvement of air quality in Nairobi and beyond through research and knowledge sharing had to be set-up, which immediately (one day after the final workshop) led to the formation of the Kenya Air Quality Network (KAQN) consisting of community members, policy-makers and scientists.

4. Discussion

We cannot compare the $PM_{2.5}$ exposures that we measured with those at Nairobi’s urban background monitoring station, as it was inoperative during our study period. This also meant that we were unable to assess whether the significant differences that we found between days in $PM_{2.5}$ exposure were due to changes in urban background concentrations or to specific local factors and activity patterns within the settlement. However, other studies in Nairobi (e.g. (Kinney et al., 2011; Ngo et al., 2015)) suggest that street-level concentrations in busy areas of the city may be 3–10 times higher than those at the rooftop urban background station. De Souza and colleagues (deSouza et al., 2017) reported mean $PM_{2.5}$ concentrations of $21 \mu g m^{-3}$ at a community centre in Viwandani, a value consistent with the lowest personal exposures of our participants. The range of median concentrations reported indoors in Viwandani by Muindi and colleagues (Muindi et al., 2016) was $10\text{--}150 \mu g m^{-3}$, a value that is also consistent with our data. However, only one previous study (Egondi, Muindi, Kyobutungi, Gatari, & Rocklov, 2016) has measured personal exposures, rather than fixed-site concentrations within the informal settlements of Nairobi. The mean exposure reported outdoors in the Viwandani settlement in this previous study was $67 \mu g m^{-3}$, a higher value than we recorded in the same area; however, this was based on researchers followed prescribed routes through the settlement, rather than community champions following their own activity patterns.

The use of citizen science approaches to involve community

Table 2

Key words used in responses to “What three things come to mind when you hear the word pollution?” in the first survey (n = 193), if word was used more than four times.

Word or phrase	Frequency mentioned
Drainage	35
Smoke	31
Diseases	26
Garbage	24
Smell	24
Industries	23
Bad	22
Air pollution	20
Dirty	20
Pollution	20
Waste	20
Air	17
Environment	17
Dust	14
Water	13
Burning	12
Sewage	12
Dumping	11
factories	9
Litter	9
Channels	8
Factory emissions	8
Pit latrines	8
Chemicals	7
Health	7
Toilets	7
Environmental pollution	6
Flying toilets	5
Food	5

Table 3

Responses to ‘Name the sources of air pollution inside your home’. This was a free text response, and only responses which were mentioned by more than four people are included.

Named source of pollution	No. of respondents
Kerosene stove	101
Charcoal jiko/stove	80
Stove (fuel unspecified)	34
Drainage/open drainage	28
Dust	21
Toilet	19
Factories	15
Outdoor polluted air	9
Tin lamp/kerosene lamp	8
Dust from outside	7
Pit latrine nearby	6
Dirty utensils	5
Untidiness in the house	5
Cigarette smoking	5

members in our research maximises the likelihood of results reflecting the real exposures of settlement dwellers, and therefore the findings may be more likely to induce personal behavioural changes which could lead to reduction in exposure. However, achieving behavioural change is notoriously difficult and not well documented (see (Barnes, 2014) for a review related to air quality). The linear model of environmental knowledge leading to environmental attitude changes leading to pro-environmental behaviour has long been critiqued as there are many other factors that help or hinder action (see (Kollmuss & Agyeman, 2002)), but environmental knowledge and values and behavioural intention are important predictors of environmental behaviour (Kaiser, Wölfing, & Fuhrer, 1999). The second way our approach could lead to reduced exposure is through policy impact via our second workshop and the subsequent formation of the KAQN, which gave the opportunity for policy-makers and other decision-makers and community champions to meet, discuss the findings and suggest future actions that could reduce

air pollution.

The mean exposures of our six participants varied by a factor of 2, and all showed a large temporal variation in exposure, with the highest exposure of each reaching 100–350 $\mu\text{g m}^{-3}$. The use of GPS allowed us to link the measured personal exposure of our participants to specific locations and activities. This revealed large spatial differences in concentration across the settlement area, and also systematic differences between champions in the areas of the settlement they used, which appear to explain differences in their mean exposure. A similar approach, linking mobile monitoring of PM_{2.5} with GPS data, has been used in Accra to identify exposure hot-spots and build predictive models of spatial variation (Dionisio et al., 2010; Rooney et al., 2012b). A key difference in our study was the engagement of community members in interpretation of the data. The community champions were able to describe the environs of particularly high or low readings, and identified the locations of many potential point sources within the settlement (as shown in Fig. 4) which may contribute to exposure. These sources are not possible to identify through other means such as aerial photographs or maps, and unaccompanied researchers would struggle not to get lost in the maze of densely packed buildings, so community member identification of sources was critical. Contributions from more generic sources (vehicles, dust, domestic emissions) and from background sources are also likely to be important, and community knowledge about cooking practices, waste burning habits etc. were useful in understanding these sources. Nevertheless, linking the spatial differences in personal exposure of our participants to the location of possible sources which they and other community members identified proved a powerful method of engaging people in the local issues.

Both our combined dataset and our outdoor data indicated significantly higher personal exposures in the evening period. A similar pattern was reported in these settlements previously (deSouza et al., 2017; Egondi et al., 2016), who found peaks in particulate matter in the morning before 6am and in the evening from 6pm using their static low-cost sensors, while Muindi and colleagues (Muindi et al., 2016) also reported higher indoor concentrations in the evening. The higher indoor than outdoor concentration may be explained by high rates of cooking in the individual home with biomass and kerosene, but indoor/outdoor location was only a significant factor when we removed time of day from our models. This suggests that use of biomass for cooking at a community level (indoors and outdoors), rather than exposure in individual homes, may explain the evening peak in exposure. Studies of personal exposure to PM_{2.5} in Accra suggest that biomass use at a community level has a much stronger effect on exposure than the choice of fuel in an individual home (Zhou et al., 2011). However, in workshops with local residents, it was also reported that visual emissions from local factories increased in the evening, when no inspections took place, a factor that has not been reported in previous studies.

There appears to be some disparity between our monitoring data, which showed generally high levels of air pollution, particularly indoors and with peaks in the settlement in the mornings and evenings during the main cooking periods, and people’s perceptions of air pollution: with two-thirds of respondents indicating they thought indoor air quality was either ‘very good’, ‘good’ or ‘neither good nor bad’ and a third rating outdoor air quality in the same way. Egondi and colleagues (Egondi et al., 2013) conducted a very large study into perceptions of informal settlement dwellers in Nairobi towards air pollution (n = 5317), and also found that more people perceived indoor air quality to be good, compared to outdoor air quality, with a majority thinking indoor air quality was moderate or good. This is of interest because it suggests that people are more concerned about the external sources of air pollution (e. g. drainage channels, surrounding industry, dust from unpaved roads etc.) which they have limited control over, compared to indoor sources of pollution, largely stoves, often fuelled in the poorest households by poor quality charcoal or wood.

There was some evidence from the questionnaires that the campaign encouraged more conversations about air pollution in the wider

settlement population. However, we did not observe increases in knowledge about air pollution in our questionnaire respondents, partly as the mobile nature of residents meant not all respondents were located a second time, and partly because our communication campaign was not as far-reaching as we hoped, due to the short length of the project. Although air pollution was mentioned frequently when people were asked what ‘came to mind’ when they heard the word pollution, other answers to this question and the lists of sources of pollution indicate that air pollution, other forms of pollution, and other environmental issues are closely linked in residents’ minds. Ngo and colleagues (Ngo et al., 2017) asked 40 residents of Mathare (an informal settlement in Nairobi) what characteristics they associated with air pollution and many said bad smell, which the authors suggested may explain why dirty water and sewage were frequently mentioned in their discussions with residents. Similarly, Egondi and colleagues (Egondi et al., 2013) reported that 81% of respondents selected ‘smelly sewage’ as a source of air pollution, and Muindi and colleagues (Muindi et al., 2014) used focus groups with adults and young people and also identified smelly drainage channels as an important source of air pollution in informal settlements in Nairobi. This may account for the prevalence of this topic in our questionnaire findings. Cleanliness was fairly frequently mentioned by our questionnaire respondents, as was also reported by Ngo and colleagues (Ngo et al., 2017); this may be because people do not see air pollution as distinct from other environmental issues.

The majority of respondents agreed that they were concerned about how air pollution affects their health, but in our first survey most people had not heard about air pollution in the preceding 6 months. In the second survey this proportion had risen, suggesting that our modest project may have sparked discussions about air pollution in the settlement. Our use of a citizen science approach may have helped here: as the community champions were walking around the settlement with visible backpacks, conversations were sparked with other community members, and champions self-reported increases in their own knowledge about air pollution. This demonstrates the value of working closely with local residents in order to raise awareness of issues such as air pollution, as well as providing a better understanding of the temporal and spatial variation in personal exposure within the settlements. Such an understanding within the community could lead to a reduction in individual exposure, for example, if people avoid hotspot areas at certain times of day, or choose alternative routes away from burning sites, for example.

4.1. Study strengths and weaknesses

This was a small-scale study, testing a new collaborative citizen science approach to assessing air pollution exposure in informal settlements, which integrated particulate matter measurement with activities to enhance community and policy-maker understanding of air pollution. There were limitations to both aspects of the study which we discuss briefly here. In terms of equipment, the Dylos sensors only have a 6 h battery life and need up to 12 h to recharge fully. This led to loss of data, because of power outages (sometimes caused by power surges due to the informal nature of the electricity supply) in the settlement. The activity log was often only completed with minimal detail, and this made identification and interpretation of indoor exposure more reliant on GPS data and less certain. Reliable separation of indoor and outdoor exposure is important in promoting understanding of air pollution sources and enhancing community understanding of measures to reduce exposure. More regular contact with community champions during the campaign might have avoided some of these problems.

Our monitoring exercise demonstrated spatial and temporal variation in exposure within the settlement. This was linked to community knowledge of formal and informal sources of air pollution, but not in sufficient detail to allow linkages between emission sources and elevated exposure to be established. The Dylos particle counters used in this study have a fairly good track record with respect to data accuracy, also in comparison with other similar devices (Sousan et al., 2016;

Steinle et al., 2015). However, it should be noted that the use of low-cost particle counters and the conversion of their particle numbers to a PM concentration does introduce uncertainty with respect to absolute PM concentrations as compared to the direct measurement of these concentrations with stationary high-precision devices. Also, highly variable micro-meteorological conditions that are typical for low-latitude environments do tend to influence the precision of low-cost PM sensors. However, the weather was fairly stable during the measuring campaign, which should have limited the impact of this problem. Future projects should design measurement campaigns in collaboration with community members to test the impact of particular locations and activities on personal exposure. However, it would be important to ensure that investigations of these links was not restricted to PM, but included other pollutants, including ammonia, which could account for the prevalence of ‘drainage channels’ and ‘flying toilets’ being mentioned by residents. Consideration of additional pollutants (such as CO and SO due to reliance on biomass and kerosene for cooking and lighting) would provide a holistic understanding of these linkages. Access to data from urban background sites, which were not available for our study, would also enhance interpretation of measurement data. This might also require more time and training for community champions; although we paid champions (who typically do not have a stable income) to encourage their participation, other time constraints might limit the involvement of any individual. Participants in our workshops were keen to know what actions they can take to reduce their contribution and exposure to air pollution, but future work needs to provide a strong evidence base to support clear messages about this.

The monitoring campaign had less impact on knowledge of air pollution in the community than we had hoped. A mural was painted on a wall in the settlement to promote the issue of air pollution, and branded t-shirts were worn by research assistants and champions, and a video was created, which helped raise awareness of the issue of air pollution. However, planned production of information panels and appearances on radio talk shows and newspaper articles did not take place, which reduced the impact of the project locally.

5. Conclusions

This study showed that a citizen science approach, commonly used in the ‘global North’, can be applied to settings such as informal settlements. Developing citizen science projects with participants, including decisions about research questions, methods, study area and communication mechanisms, is one way of ensuring projects are relevant to people’s lives, as monitoring takes place in the spaces they regularly visit and messages about results are disseminated in a relevant way. From an engagement perspective, the study sparked discussions about air pollution between residents and policy-makers, as well as scientists and urban planners. The workshops provided a new and much-needed forum to bring together for the first time community members, local policy makers and government officials, and researchers to discuss air pollution in Mukuru. They provided space for discussion of issues such as the smell of pollution after dusk, which a local resident attributed to the fact that air pollution monitoring by the government only takes place during the day, so polluting activities take place after dusk. As well as bringing key stakeholders and different voices together, such workshops may help to reduce the feelings of helplessness about air pollution identified by Muindi and colleagues (Muindi et al., 2016) in their focus groups, by giving residents space to discuss issues with local leaders.

A key outcome from this workshop was the formation of the Kenya Air Quality Network (KAQN), as participants realised there was a need for a multi-stakeholder forum to discuss air pollution in Kenya. Ever since, the KAQN has met quarterly, with SEI Africa acting as its secretariat. Since 2016, public health agencies have become involved in the network and industry representatives have been invited to annual conferences; engaging these parties will further enhance the impact of the network. The formation of the KAQN as a result of this project has

helped to drive research and action forwards, not just in this settlement, but in Kenya and neighbouring countries more widely. To date, three further action-oriented research projects on the topic of air pollution in Mukuru have been funded, with the KAQN helping both steer the direction of the research and act as a mechanism for enacting change as a result of project findings. In 2018, Kenya County made the decision to designate Mukuru as a “Special Area for Planning” and upgrade the settlement, partly due to the high levels of pollution in the area highlighted through these studies and the KAQN. Regular engagement between researchers and the County government, initiated by this project, has also led to the County developing an air quality management policy.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apgeog.2019.102133>.

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