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Low-Cost Sensors for Air Quality Monitoring in Developing Countries – A Critical View

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Abstract: Air quality monitoring in developing countries is in a dismal state. The monitoring of ambient air can be done by conventional/fixed stations and recently emerging low-cost sensors. The study first discusses the low-cost sensor and its differences with respect to conventional sensor. The existing network employing low-cost sensors have been explained in detail to create a better understanding. While deploying these sensors in developing countries one can open a plethora of opportunities; it also poses a number of challenges required to be dealt with, for effective monitoring of air quality.

Key words: Air quality monitoring, developing countries, low-cost sensors, community monitoring, exposure assessment.

Introduction

Air pollution is considered one of the biggest problems to tackle with in the recent times in developing as well as developed countries. The impact of the ambient air pollution is estimated to be larger in developing countries (WHO, 2005; Wheeler, 2001). The megacities in developing countries e.g. New Delhi, Mumbai, Chennai, Bangkok and Beijing are experiencing frequent violation of ambient air quality standards (Baldasano et al., 2003; Wang and Hao, 2012; Gurjar et al., 2016; Souza et al., 2013). In developing countries, the situation is worse owing to a number of reasons: lack of funds, resources, expertise and awareness; and laxity in framing and implementation of rules and regulations (Gulia et al., 2015; Han and Naeher, 2006). Deterioration in ambient air quality has been linked to health impacts in human beings e.g. elevated concentration of particulate matter (PM) may result in numerous health problems including cardiac problems, lung cancer and heart disease leading to mortality (Gurjar et al., 2010). In a report from World Health Organization (WHO, 2014), about seven million deaths were estimated worldwide for the year 2012 owing to increased concentration of $PM_{2.5}$.

To understand the extent of the problem it becomes vital to understand it, which can be accomplished by monitoring the ambient air quality. In developed countries, monitoring is done by fixed monitoring stations having a rigorous operational and calibration regime (Snyder et al., 2013). High quality data obtained from these stations can be used for various purposes e.g. regulative purposes, exposure assessment, community monitoring and awareness. Short-term monitoring is also possible by mobile stations (Kumar et al., 2015). Generally, the capabilities of these mobile stations

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match with those of fixed stations. These mobile stations can be stationed at a desired location to collect air quality data for a short-term duration. Of course, their limitation is the data collection over a short period (Devarakonda et al., 2013).

Now, the air quality monitoring is shifting towards low-cost sensors in developed world (Snyder et al., 2013). Some of the obvious reasons are: low-cost, larger extent of temporal and spatial variation of air quality and instant results. For these advantages, the developing countries may want to turn towards low-cost sensors for air quality monitoring. However, the practice of utilizing low-cost sensors for air quality monitoring is still evolving and this study discusses the opportunities and challenges encountered while deploying low-cost sensors for monitoring the ambient air in developing countries.

Air Quality Monitoring in Developing Countries

With time, the developed countries have established reliable networks of air quality sensors (AIRNOW, 2016; Defra, 2014). An ambient air quality station in a developed country may generally include ultraviolet photometers (for measuring O_3), chemiluminescent instruments (for monitoring NO_2), tapered element oscillating microbalance (for PM_{10} mass) and acid/aerosol sampler (for sampling $PM_{2.5}$ and gaseous acid components) (Peters et al., 1999). On the other hand, most developing countries of Asia and Africa are still languishing with very basic monitoring or no monitoring at all (Roychowdhury et al., 2016).

In general, the air quality monitoring in developing countries is designed to ensure compliance with the regulatory standards for the pollutants e.g., in China, about 2000 stations in more than 100 cities are maintained by CNEMC (Gulia et al., 2015) for air quality monitoring. In South Africa, there are about 90 monitoring stations country-wide to report the air pollutants' level (DEA, 2011). According to a report from Greenpeace (Greenpeace, 2016), there were only 10 monitoring stations in Thailand having the ability to measure $PM_{2.5}$.

In India, the situation is grim for air quality monitoring, similar to other developing countries. There are more than 5,000 cities and towns in India, out of which some kind of monitoring mechanism exists in 268 only as reported by Roychowdhury et al. (2016). Furthermore, Central Pollution Control Board (CPCB), the regulatory body for environmental concern in India reports that there are 133 monitoring stations. Out of these 133 stations, there are 119 from which live data can be obtained. Delay is being reported in case of six stations and eight stations are inactive (CPCB, 2018). India has also recently launched its first air quality index to create awareness in general public about the problem of air pollution (Basu, 2016). Furthermore, a lot of research in India now focuses on ambient air pollution and its mitigation (Chinthala and Khare, 2012; Gulia et al., 2018).

The main reasons that have been held responsible for poor air quality monitoring in developing countries include (Awe et al., 2017): lack of demonstration of the connection between reducing air pollution and improving public health; lack of human and institutional systems required to utilize the monitoring equipment; lack of provision for consumables, operation and maintenance while estimating costs for the equipment; lack of quality assurance for the data collected; and lack of inclusion of all the stakeholders in planning, analyzing and decision-making.

Low-cost Sensors for Air Quality Monitoring

Low-cost sensors are currently available to measure a range of air pollutants (Snyder et al., 2013; Aleixandre and Gerboles, 2012). There are two types of air pollutants mainly: gas phase species and particulate matter species. Commercial available sensors measuring gas species operate through light absorption or electrochemical interaction (McKercher et al., 2017). The sensors for particulate matter generally employ light absorption or scattering for monitoring (Kelly et al., 2017). These individual sensors need to be integrated into a sensor board. A sensor board typically consists of sensors for gas phase species and particulate matter species, global positioning system (GPS), general packet radio service (GPRS) antenna and other paraphernalia for inter-connections and data storage. The main differences between conventional sensors and low-cost sensors have been highlighted in Table 1.

Application of Low-cost Sensor

Although major spectrum of air quality monitoring is covered by static and high-end monitoring stations across the world, the usage of low-cost sensors is increasing day-by-day. A number of networks are already in operation in developed and developing countries employing low-cost sensors for measuring

Table 1: Comparison of fixed stations and low-cost sensors for air quality monitoring

Feature	*Conventional sensor*	*Low-cost sensors*	*Reference(s)*
Cost per sensor	Very high (US$ 500-5000)	Low (US$ 20-100)	Jiao et al., 2016; Kelly et al., 2017
Installation	Difficult	Easy	Lin et al., 2015
Amount of data collected	Less	High	Devarakonda et al., 2013
Area coverage	Low	High	Marjovi et al., 2015
Installation density	Sparse	Dense	Mead et al., 2013
Data quality	Repeatable and reliable, complying with air quality directive (EU, 2008)	Not complying with air quality directive (EU, 2008)	Schneider et al., 2017; Snyder et al., 2013; Spinelle et al., 2017; Spinelle et al., 2015
Post-processing of data	No or minimum post-processing	Rigorous processing	Schneider et al., 2017; Spinelle et al., 2017; Spinelle et al., 2015
End user for data collected	Research institutions, policy-makers	Citizens, local government	Snyder et al., 2013; Kumar et al., 2015

the levels of air pollution. Opensense and Citi-sense are two such networks being operated in Switzerland.

In Opensense network, the sensors are mounted on public transportation – buses, trams etc. The sensor board installed on buses include GPRS & GPS antenna, data-logger, chemical sensors (CO sensor, CO_2 sensor, ozone sensor), temperature and humidity sensor and nitrogen dioxide sensor. In addition, the network also uses crowd-sensing (a concept equivalent to crowd-funding), in which smartphones equipped with sensors are used for collecting data. After collecting the data, data is filtered and processed subsequently. With the help of filtered data, models are built to interpolate, and hence better understand and interpret the air quality. Finally, the inferred information is sent to the end users (e.g. individuals from the locality, local government, research organizations). Additionally, if an episode of air quality occurs, then information may be sent in real-time to the end users.

Another such project is Citi-sense (http://www.citi-sense.eu/). The network directly engages citizens to ensure benefits in terms of air quality, environmental quality of public spaces and indoor air quality in schools. It develops citizens' observatories to contribute to and participate in environmental governance, to support and influence community and associated decision-making. In these observatories, citizens can get access to real-time data about the local and global environment, communicate further their own observations and influence policy-makers in their area. Citi-sense works with the concept of "sensors-platform-products-users", where technologies for distributed sensing represent sensors; information and communication technologies are the platforms; information products and services indicate products; and users are defined by citizen involvement in collecting and reporting the air quality data. The network combines high-quality environmental technologies for sensors, ICT clout platform with internet of things (IoT) and data mining to create useful information for the end users. The products include air quality maps for spatial interpolation and visualization and alert services for pollution hot-spots.

Additionally, there are a number of networks using low-cost sensors nowadays e.g. AirVisual, AirCasting (Castell et al., 2017), OpenAq (Openaq, 2018) and PurpleAir (PurpleAir, 2016) employing citizen participation in data collection and decision-making.

In India, IndiaSpend's Breathe initiative is one of the organizations running a network of independent air quality monitoring devices across India (http://api.indiaspend.org/dashboard/). The sensors have been deployed in 15 cities for monitoring of air quality. Low-cost sensors can automatically and continuously stream data through Global System for Mobile communication (GSM) module (IndiaSpend, 2017).

Opportunities and Challenges

Conventionally air quality monitoring stations are costly, take a lot of space for installation and operation and are difficult to operate. So it is generally difficult to install them in large number. As a result, the measurements are interpolated to estimate the air pollutant concentrations at the points located far away from the station. The interpolated results may not represent the actual values on the field. The smaller commercial sensors can be strategically installed closely for measuring the pollutants at the micro level (Aleixandre and Gerboles, 2012).

The concept of low-cost sensing can broaden the horizon of environmental measurement by making the installation of sensors feasible at a large scale and from the participation of community groups, non-governmental organizations and citizen scientists in collecting, analyzing and reporting the air quality data. Thus, new sensors may solve the limitation of traditional monitoring by: (i) increase in area coverage and extent of air quality monitoring in developing countries and (ii) extension of the existing air quality monitoring programmes to under-represented areas for the developed countries (Reis et al., 2015).

The low-cost sensors are liable to be used in higher number of locations as compared to their conventional counterpart. This arrangement may be helpful in a number of ways e.g. it is feasible to perform high resolution exposure assessment with the data collected. As these sensors also collect local weather data, more accurate input conditions can be obtained for air quality modelling providing robust conclusions. Other purposes for which these sensors can be utilized are: emission inventories, detecting pollution hot-spots and conveying real-time exposure assessment to the general public (Snyder et al., 2013).

For developing countries, it may be more beneficial to install these low-cost sensors owing to these sensors being economical. Also, sample collected from fixed stations need complex instrument for analysis e.g. gas chromatograph. Such analysis requires expertise in terms of manpower and laboratory facilities. On the other hand, in case of developing countries, laboratory facilities and human expertise are scarce, making the operation of these fixed sensors cumbersome (Awe et al., 2017; Wang and Hao, 2012). Furthermore, the older parts of cities and towns in developing countries have narrow streets (Cervero, 2013), which sometimes have the worst air quality due to fewer air exchanges. The setting up of fixed station is more difficult in such areas and it may be prudent to install smaller low-cost sensors for air quality monitoring in such areas.

A number of challenges are associated with the use of low-cost sensors. The prominent challenge is the reliability of the measured values for air pollutants (White et al., 2012). The gas sensors employ a number of chemical/physical phenomena e.g. oxidation/reaction, oxygen adsorption, change in dielectric constant and light absorption for measuring the pollutant concentration in air. These reactions may get easily affected by operating conditions e.g. temperature and relative humidity, and natural chemical reactions occurring in the atmosphere. These variations may be diurnal and seasonal. Consequently, the correction factors provided by the manufacturers may not be suitable in most of the cases (Jiao et al., 2016; Castell et al., 2017; Shallcross et al., 2009).

In addition, the low-cost sensors available today does not have the capability of measuring ultrafine particles and nano-particles (HEI, 2013; Singh et al., 2010; Kumar et al., 2010). Although, there are low-cost sensors available for the measurement of particulate matter, their reliability in case of lower concentration is more questionable (Kelly et al., 2017). Such measurements would help linking the excess occurrence of these pollutants in ambient air to the diseases caused by them.

Furthermore, these sensors do not last long – their working life ranges from months to a few years. Operation may be tricky due to the costs associated with data storage, analysis and interpretation. Similarly, maintenance may be costly as a result of the need for frequent calibration and battery replacement. Future challenges also lie in persuading the scientific community and policy-makers to accept the new technology. Before deploying these sensors on a large scale, it is necessary to create awareness and impart training to the stakeholders involved (Schneider et al., 2017). Yet another challenge may be dealing with the increased amount of e-waste arising out of use of these sensors. The challenge may be bigger for the developing countries which are dealing with their own e-waste in addition to the imported one from developed countries (Nnorom and Osibanjo, 2008).

Conclusions

Air quality monitoring has been inadequate in the developing countries with the use of fixed monitoring stations. The recent use of low-cost sensors for monitoring the air quality brings a sea change in the paradigm of the air quality monitoring. Owing to their low-cost, larger coverage, ability to capture temporal and spatial heterogeneities in air pollutants concentration, these sensors are being considered a panacea for the problem of lack of air quality monitoring in developing countries. Quite a number of networks have been established in developed countries and a few in developing countries deploying these sensors.

These sensors provide a plethora of opportunities for the developing countries: economic feasibility for establishing networks in rural areas or smaller towns; broadening the horizon of existing monitoring networks; possibility of inclusion of all the stakeholders in environmental decision-making; communicating real-time exposure assessment to the general public; feasibility of installation in narrow streets of older areas of the urban centres. The challenges associated with the low-cost sensors are: measurements being less reliable and non-compliance with the regulatory directives e.g. European directive on air quality; effect of diverse environmental conditions on the pollutant estimations; working life; need for frequent calibration and battery replacement; inability to measure ultrafine and nano-particles; need for data storage and post-processing and, e-waste from the discarded sensors.

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