Air pollution and vulnerability: solving the puzzle of prioritization

Abstract

While ambient air pollution levels in excess of prescribed health standards are generally unacceptable, the exceedance is even more serious in areas where people reside. Vulnerability caused by poverty, disease, lack of education and poor living conditions exacerbates the problem. Air quality management plans identify prioritized strategies for improved air quality independent of consideration of vulnerability. A population exposure and vulnerability risk prioritization framework comprising five themes (air pollution sources and levels; air pollution potential; community awareness, observations, perceptions and actions; and vulnerability factors) was proposed and applied to the eThekwini Municipality (Durban). Data were scored according to pre-determined risk threshold values to ascertain at-risk communities. While those urban wards located in a known air pollution hotspot had the highest air pollution levels, a peri-urban ward with moderate exposure levels was most vulnerable. This framework will prove invaluable for the development of focussed interventions to reduce vulnerability and air pollution associated adverse health impacts (154 words).

Introduction

Air pollution is a major environmental health threat to humans, especially for children in whom respiratory function is still developing (Liu & Zhang, 2009). Exposure to several air pollutants, i.e. sulphur dioxide, nitrogen oxides and particulate matter, is a known risk factor for acute and chronic respiratory infections (Balmes, Fine & Sheppard, 1987; Kagawa, 1985; Kampa

& Castanas, 2008), as well as other diseases including myocardial infarction, ischemic stroke, and cardiopulmonary disease (World Health Organization, 2004).

To manage ambient air quality and thereby protect the health of the South African population, South Africa enacted the National Environmental Management: Air Quality Act No. 39 of 2004 (NEM AQA). This legislation marks a paradigm shift in the manner in which air quality is managed in South Africa and for the first time presents an opportunity to include human health considerations. Each South African local municipality is required to draft and implement an air quality management plan (AQMP) with the aim of maintaining ambient air quality levels below specified standards for criteria pollutants and thus minimise adverse human health impacts.

While the presence of a community is considered for the site selection of monitoring stations within the guidelines of an AQMP, community characteristics, such as vulnerability, are not. Vulnerability is the level of exposure of human life, property and resources to the impact from hazards (Adger, 2006; Fussel, 2007; O'Brien, Quinlan & Ziervogel, 2009). Vulnerability may be defined as "the interface between exposure to the physical threats to human well-being and the capacity of people and communities to cope with those threats" (Department of Environmental Affairs and Tourism, 2006). Vulnerability has two components: 1) external risks, shocks, and stresses to which an individual or household is subject, and 2) internal abilities which offer the means for coping without causing damage or loss. Although vulnerability is often considered in relation to a particular stressor or hazard, such as drought, it is becoming increasingly clear that it is generated and shaped by interacting biophysical and socio-economic factors (Department of Environmental Affairs and Tourism, 2006). Moreover, communities, or individuals within a community may not be equally vulnerable (Makri & Stilianakos, 2008;

O'Brien, Quinlan & Ziervogel, 2009). Vulnerability is strongly linked to the complex make-up of society, including socio-economic gender and age characteristics; past loss and misfortune; and susceptibility to future losses (Adger, 2006; Makri & Stilianakos, 2008). It may be compounded by several factors including location; self-protection - the capacity to protect oneself from harm including access to materials, knowledge, access to information; and social protection - the extent of assistance and support, including services, resources and technical expertise, that society can provide (Department of Environmental Affairs and Tourism, 2006).

The aim of this research was to develop an air pollution population exposure and vulnerability risk prioritization framework for potential use by air quality managers in conjunction with their AQMPs. The framework included vulnerability factors such as disease, lack of education and poor living conditions, all of which are important in areas occupied by moderate to low socio-economic status communities. In this way, high-risk areas in terms of air pollution health impacts were identified using a specifically-tailored set of indicators that assessed ambient air pollution, population exposure, demographic and vulnerability factors, and subsequently prioritised specific local communities at greatest risk. The identification of these high risk areas and communities will lead to focussed management of the area and development of interventions to reduce adverse health impacts.

Methods

The proposed framework (Figure 1) was derived through the review of several sources (including air quality indices, air quality policy documents and AQMPs), and informed by three main theories: Risk Assessment, Human Health Risk Assessment and DPSEEA (Driving force, Pressure, State, Exposure, Effects, Action) - a framework developed by the World Health

Organization that brings together the environment and health with action-based outcomes at appropriate intervention levels (Corvalan, Briggs & Kjellstrom, 1996). The framework was adapted to meet the specific needs of a developing country.

A systematic approach was adopted. Five themes were identified and indicators developed by theme. The themes were (1) air pollution sources; (2) ambient air pollutant levels; (3) air pollution potential; (4) community awareness, perceptions, observations and actions (all included in Table 1); and (5) population vulnerability factors including population exposure (Table 2). The purpose of the framework was to assist air quality managers of district or local municipalities to identify at-risk communities in terms of air pollution exposure and vulnerability to thereby allocate resources and prioritise service delivery to alleviate risk conditions and assist communities to better cope with their situations. An important consideration for all indicators was that there were local data available for application in the framework and that the use of the framework was simple yet efficient at identifying vulnerable communities exposed to high levels of air pollution.

The main source of data available was derived from Statistics South Africa's census database (Statistics South Africa, 2007). A review of vulnerability literature, studies focusing on environmental and social problems in South African low-income communities and air pollution monitoring and research in South Africa was carried out. Then, a careful and thorough investigation of the census database was made to look for measures that overlapped with those considered essential measures of vulnerability identified in the literature. The resulting set of indicators may not be inclusive of all possible indicators of vulnerability. However, the framework is a practical, composite tool to assist decision-making by linking vulnerability and air pollution exposure health effects.

Air pollution sources

Three main air pollution sources were defined according to those outlined in the National Framework for Air Quality Management in the Republic of South Africa (2007): point (e.g., stacks and vents) and non-point (e.g., mining activities and stockpiles) **industrial** sources; **mobile** sources (i.e., vehicular emissions from cars, buses, boats, planes etc) along roads; and non-point **agricultural** burning.

Ambient air pollutant levels

The criteria pollutants of concern, identified by the Department of Environmental Affairs and Tourism are sulphur dioxide, nitrogen dioxide, carbon monoxide, particulate matter, ozone, lead and benzene. Other pollutants are also detrimental or hazardous to human health, such as some hydrocarbons; however, they are presently not included in the Department's list of criteria pollutants (National Framework for Air Quality Management in the Republic of South Africa, 2007) nor included in the ambient air quality guidelines (Department of Environmental Affairs and Tourism, 2006).

Air pollution potential

Air pollution potential is the meteorological potential for the development of high pollutant concentrations in an area and at a given location depending on the amount of pollutants emitted and the atmosphere's ability to disperse them. Factors included stability, wind speed and direction, mixing depth, ambient air temperature, topography, solar radiation and humidity.

Wind speed is an important factor influencing ambient air pollution levels in that it affects dispersion and therefore pollution concentrations in different areas. Lower wind speeds lead to calm, stable conditions with little chance of dispersion occurring hence higher concentrations as pollution accumulates (Holzworth, 1967). The values implemented for high risk (most vulnerable), moderate risk and low risk were less than 2 m sec^{-1}, 2 - 4 m sec^{-1} and greater 4 m sec^{-1}, respectively (Diab, 1978). Mixing depth may be defined as the vertical distance between the ground and the altitude to which pollutants are mixed by turbulence caused by convective currents (Holzworth, 1967). The shallower the mixing depth is, the greater the accumulation of air pollution and higher concentrations to which people on the ground may be exposed. Mixing depth does not vary significantly across a city but does vary seasonally. Therefore, for the purposes of the model, all communities within a single metropolitan area were allocated the same average annual mixing depth from a range of less than 500 m, 500 m - 1 km and greater than 1 km (Diab, 1978).

Solar radiation plays a role in the formation of secondary pollutants by photochemical reactions. Clear sky conditions coupled with high temperatures cause hydrocarbons and oxides of nitrogen to react and form secondary photochemical pollutants such as ozone. Solar radiation received at the surface in South Africa varies geographically, seasonally and depending on atmospheric conditions, i.e. clouds, dust, and water vapour. In January, maximum values may exceed 34 MJ m^{-2} day^{-1}. Since solar radiation does not vary significantly across a city, an average annual solar radiation value was allocated for all communities.

The water vapour content of air is measured as a percentage of the saturation vapour pressure of water at a given temperature and is termed relative humidity. The amount of water vapour in the atmosphere is highly variable and depends on geographic location, proximity to

water bodies, wind direction and ambient air temperature. In South Africa, relative humidity is generally highest on the East coast and during summer when temperature and rainfall are also at their highest. Water vapour plays an important role in photochemical reactions in the lower atmosphere which leads to the formation of secondary pollutants. However, similar to solar radiation, humidity levels do not vary significantly across a metropolitan area and therefore average annual humidity percentages were identical for all communities within the same metropolitan area.

Nocturnal temperature inversions occur in a valley (in the valley basin) when the temperature of the atmosphere increases with altitude compared to the usual decrease with altitude. An inversion layer of cooler air rests between warmer air below and above it, trapping air pollutants at ground level and, coupled with low wind speeds, increases ground level pollution concentrations. A community located on the floor of a valley was more likely to experience a nocturnal temperature inversion than a community found on the valley slopes, hence the presence or absence of valley floor conditions was included as a measure.

Population vulnerability factors

Five broad subsections were identified for population vulnerability: 1) general (population demographics), 2) health, 3) exposure, 4) socioeconomic, and 5) environmental disasters and social risks. Population demographics provide an indication of the changing characteristics of a population. In South Africa, Statistics South Africa conducted a national survey of population demographics including average age, sex and household income in 1996 and 2001 (Statistics South Africa, 2007). Certain population demographics may be used to measure vulnerability to health hazards, specifically exposure to excess air pollution, since they

have a direct or indirect influence on an individual's, household's or community's ability to cope. These include enumeration area type, population density, age, sex, population group, and socio-economic status, incorporating highest education level, employment status and annual household income. General health is an important determinant of livelihood and hence vulnerability includes incidence and prevalence of diseases (specifically respiratory diseases and HIV/AIDS), nourishment, access to health care and life expectancy. Absence of or inadequate supply of services may lead to personal exposure to several environmental health risks. Waterborne diseases, contaminated waste and indoor air pollution are the most common health hazards in low-income communities (Department of Environmental Affairs and Tourism, 2006). Therefore, three service factors included were sanitation (i.e., refuse disposal), energy use and main water supply.

Community awareness, perceptions, observations and actions

Several qualitative measures, more difficult to measure and compute, were deemed relevant for inclusion since they provided an important indication of local happenings and community awareness, perceptions, observations and actions. This complex subsection was designed such that presence or absence of the specific indicators such as complaints and media articles, indicated risk or no risk, respectively. All industries with industrial point sources are required to maintain an air quality complaints register. Moreover, some communities have established their own complaints lines, such as the South Durban Community Environmental Alliance (SDCEA) - a democratic coalition of members of several communities who have struggled together to bring higher environmental standards to the industries and communities that cohabit South Durban. In this area of South Durban, air pollution is a major environmental

problem, and the occurrence of complaints made to SDCEA as well as large industries with complaints hotlines is a reflection of the extent of the problem.

The media is a universal means for conveying information about public dissatisfaction towards environmental pollution. Members of the public or of an action group may express their opinion about an air pollution problem, and even the presumed source of the problem, to a newspaper or magazine who then prints the story or letter. In this way, the problem is made known to a broader part of the community, and may also place pressure on the presumed source to find ways to alleviate the problem. The existence of such letters, written by the community, environmental activists, industry or any other individual or institution, is included in the framework as 'presence or absence of media articles pertaining to air pollution and air pollution complaints'. This information was sourced using archived media articles available online and through personal records kept by the air quality manager.

Other examples of community awareness, perceptions, observations and actions may include the initiation of a NGO such as SDCEA to assist local communities to oppose poor air quality in their living and working environments. Also, local knowledge of recent disasters (e.g. oil tank explosions etc) and public uneasiness of residential proximity to high risk industrial zones are relevant factors to consider. They provide a snapshot of community perceptions of air pollution issues and when these perceptions are extremely negative or emotive this may exacerbate the problem, for example, by pressuring local industries into remedial action. Finally, the existence of public information campaigns providing environmental health advice to community members improves awareness and may encourage individuals to take action to protect their health.

Case study – eThekwini Municipality

The eThekwini municipality is part of the Durban Metropolitan Area and is found on the East coast of South Africa in the province of Kwazulu-Natal. Approximately 33 % of the province's population reside in the municipality. The city of Durban, and particularly the South Durban basin, is the second largest industrial hub in the country. Air quality in the municipality is managed by the Pollution Control Support and Risk Management: Health Unit.

An AQMP for the municipality, but with specific emphasis on South Durban (home to two major oil refineries, a paper mill, an international airport, a sewerage treatment plant, a heavily trafficked motorway, several landfill sites and small-scale mills, manufacturing and processing plants), was developed in 2006. Furthermore, these activities border directly on several residential areas, especially low-income communities including Jacobs, Isipingo, Clairwood, Merebank, Wentworth, Umlazi, Amanzimtoti and Umbogintwini.

Few formal epidemiological studies to assess the health status of community residents exposed to excess ambient pollution levels have been carried out in South Durban. Informal studies include a journalistic investigation into leukaemia cases, an unpublished thesis on child chest complaints, and observational evidence of pollution and odours and subsequent side-effects such as headaches and burning sensations in the eyes, nose and throat (groundWork, 2003). A formal study known as the 'Multipoint Plan: Project 4 South Durban Health Study' was recently undertaken in South Durban (eThekwini Municipality, 2006). This included both an epidemiological study and health risk assessment. Results indicated that several moderate concentrations of four priority air pollutants were strongly and significantly associated with reduced lung function in child asthmatics and genetic alterations producing reduced ability to

cope with oxidative stress. Children residing in the southern parts of Durban were at greater risk of developing persistent asthma and airway hypersensitivity than children in the north.

Pressure from government, community members and action groups resulted in the initiation of several monitoring campaigns. The eThekwini municipality contracts the Norwegian Institute for Air Research (NILU) to monitor air quality at 15 measurement stations around the city. Air pollutants monitored include nitrogen oxide, nitrogen dioxide, ozone, particulate matter (diameter equal or less than 10 micrometers), sulphur dioxide and total reduced sulphide. The Durban South SO_2 Steering Committee operates several continuous sulphur dioxide monitoring stations and the two oil refineries monitor stack emissions of sulphur dioxide. Community monitoring is headed by the SDCEA.

This municipality was selected as an ideal case study candidate since several data sources exist, an AQMP is in place, small research studies have been undertaken and there is public willingness to ensure air quality managers prioritise resource allocation to reduce community vulnerability to excess air pollution. There are 100 wards in the eThekwini municipality. Seven of these wards were selected for inclusion in the case study based on their location. Four were peri-urban wards located in the far North of the municipality and three were urban wards in the South Durban basin. The peri-urban wards include Cato Ridge, Ximba, Nkandla, Sthumba and Nonoti (ward 1); Mgezanyoni, Mgangeni, Inanda and Mshazi (ward 2); Hammarsdale, Drummond and Inchanga (ward 4); and Mophela/Georgedale and Sankontshe (ward 5). The urban wards include Wentworth and Brighton Beach (ward 67); Mobeni, Jacobs, Austerville and Merewent (ward 68); and Durban Airport Area, Isipingo Beach and Orient (ward 90). Data were extracted for each of the seven wards and entered into Microsoft Excel spreadsheets programmed to score each indicator, determined by a given threshold value and associated score. ‘Presence

of' for an indicator was coded yes: 3 and no: 0. Where threshold ranges were possible, greatest risk was assigned '3', moderate risk '2' and minimal risk '1'. In most cases, 'no known risk' or 'no available data' was assigned '0'. Although this is not desirable, it is reiterated that the framework is planned for use by air quality managers and a simple scoring system was preferred.

Results and Discussion

Results of the scored indicators for each of the five themes and overall totals are provided in Table 3. The ward with the maximum scores for four of the five themes (population vulnerability factors theme excluded) was 'Mobeni, Jacobs, Austerville and Merewent'. The peri-urban ward of 'Mgezanyoni, Mgangeni, Inanda and Mshazi' was identified at greatest risk using the specified indicators for population vulnerability. Three of the four wards scored equally for the community factors, probably since they are located within close proximity to each other and share the efforts of a combined community action group (i.e. SDCEA).

There was some evidence of the three peri-urban wards being potentially at greater risk in terms of the vulnerability factors compared to the urban wards, although the range in scores was relatively small (44 – 52). Ambient pollutant levels for the peri-urban wards were determined using a proxy peri-urban monitoring station since no stations are presently located in any of the four wards. The proxy peri-urban station used was located in the suburb of Alverstone (ward 9) and measures background air quality levels for the city of eThekwini. Since the emphasis of the framework's application is on air pollution, it would be beneficial for the current monitoring network to extend its range and include a new station in the Cato Ridge area to monitor air quality levels in an area that includes light industry, chicken and crop farming.

The three themes: air pollution sources, ambient pollutant levels and air pollution potential, were combined and weighted as 75% of the total score for each ward. The remaining 25% was allocated to population vulnerability factors (20%) and community factors (5%). This weighting was chosen since air pollution is the main environmental health risk of concern. These results are provided in Figure 2. There was no significant alteration in the ranking of the wards by greatest risk when the results were weighted. The main reason for this is that the number of indicators in the ambient air pollutant theme is large therefore generating a large subtotal score even though many of these data were not available (either not measured or missing). An improvement to the framework may be to select some of these indicators for inclusion and exclude those pollutants not regularly monitored, even though included in the national standards such as the number of exceedances in a 24 hour period for lead.

The proposed air pollution population exposure and risk prioritization framework was applied to the eThekwini municipality to assess indicator feasibility, data availability and ease of application. Several suggested indicators were not viable because the required data were unavailable. ‘Proximity of community to air pollution source’ was excluded since there was more than one community per ward; ‘number of vehicles on nearest road per hour and per annum’ was excluded since there were no data available; ‘percentage of nutritional problems’ was changed to ‘nutritional problems present or not present in ward’; ‘proportion of schools feeding children’ was changed to ‘school included in government feeding programme’; ‘Grade 12 level of education’ was changed to Grade 7 or higher to better reflect the education level of the communities surveyed; ‘annual household income’ was changed from annual to monthly household income and ‘area per capita of open or recreational space’ was changed to ‘open or recreational space present or not present in ward’.

Data collection was lengthy since this was the first time the framework was applied but future applications will only require that data are updated where necessary. Proxy data were used in many cases since data were not available at the appropriate resolution (i.e., ward level). Improvements to the framework's efficacy will be possible when these data are made accessible. Other problems encountered during the data collection and management phase included not knowing which institution to contact for the required data and lengthy time delays in obtaining data. When data were supplied, no indication was provided of its uncertainty or specific collection methods. These factors contribute towards the overall uncertainty of the framework's results. Since no similar work has been carried out, fixing threshold values was extremely difficult. The nature of the available data led to the subsequent altering of indicators and associated threshold values after searching for possible comparatives in other countries. For example, the indicator 'incidence of other communicable diseases' was replaced with 'incidence of diarrhoea in under 5 year old children per 100 000' since these data are considered to better represent a vulnerable community (Briggs, 1999). Many of the original indicators were removed from the framework since the data were not available or the means for collecting the data were too difficult or time consuming. For example, the indicators 'proximity of the community to the nearest road' and 'type of road' were removed. At ward level, there were multiple communities in each ward; however, these were not delineated clearly on any map. In this instance, a site visit would probably be best to collect and verify these data. This might not be possible for the air quality manager. An attempt to ground-truth the collected data was made by contacting a sample of local residents in the each of the seven wards. Data verified in this way included indicators for recent disasters, means for complaints to be made and presence of action groups, and schools provided with food by the Department of Education.

Conclusion

Despite its limitations, this framework provides a first attempt to quantify vulnerability among communities parallel to personal exposure risk to air pollution. The framework was applied to the eThekwini municipality to assess indicator feasibility, data availability and ease of application. Several suggested indicators were not viable and proxy data were used in many cases because the required data were not available. Improvements to the model's efficacy will be possible when these data are made accessible and measures of data certainty are included.

Of use to air quality managers is the ranking of wards for prioritization. This knowledge may be used to develop interventions specific to identified factors. For example, overall the peri-urban wards were most vulnerable, in terms of vulnerability factors, and possible interventions should target service delivery and healthcare provision in these areas. The lack of air quality monitoring equipment in the most vulnerable wards is also reason for concern since it is unknown whether their existing vulnerability is exacerbated by poor air quality. Future work will entail refinement of the framework and possible application in a second municipality to test indicator robustness, current threshold values appropriateness and overall usefulness for air quality managers.

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