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Original article

# A criticality index for air pollution monitors

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ABSTRACT

In this paper, we develop a criticality index for air pollution monitoring networks. The index quantifies the effect on the system of removing an air pollution monitor, which is calculated as a weighted sum of the differences between baseline values interpolated with historical data using the entire monitoring set and values interpolated with each monitor independently removed from the set. The interpolation procedure tests for linear dependencies in the north-south and east-west direction and then universal kriging is selected when linear dependencies exist, otherwise ordinary kriging is applied. The index's cost function is evaluated on a regular grid. The cost function includes a multiplication factor when false-positives or false-negatives above an air quality standard are introduced because of the removal of a monitor. The sensitivity analysis indicated the final index ranks were not sensitive to variations in the multiplication factors. The index captures the effects of wind direction in the study area. We apply the index to an industrial air pollution monitoring network in Hamilton, Ontario, Canada, which consists of eight air pollution monitoring units measuring $PM_{10}$. We find a large difference in the cost with a minimum of 91,087 to a maximum cost of 1,733,835 or 0.052 and 1.00, respectively, for the proposed index. The removal of the monitor with the highest index value would have a significant effect on the network compared to the impact of removing any of the other seven monitors.



## 1. Introduction

The complexity of modern society relies on many systems to function including power generation, natural gas, telecommunications and transportation networks. These networks are examples of critical infrastructure (Rinaldi et al., 2001). The importance of these networks makes it necessary to plan for potential disruptions caused by partial or complete network outages (Brown et al., 2005; O'Reilly et al., 2006). An index is often applied to quantify the results from a network evaluation, where a value is calculated for each asset in the system. The index can be calculated with a single criterion or with multiple criteria. For example, Sullivan et al. (2010) determined the rank-order for increased travel time when each road link was individually removed from a transportation network. Stakeholders can use the index values to plan for future capital replacement costs or potential outages and to identify areas without appropriate coverage. Air pollution monitoring also relies on networks of monitors that are designed to function as a system.

Urban air pollution is generated, dispersed and eliminated by many processes that combine to produce spatially variable concentrations (Adams et al., 2012). These spatially variable fields are ineffectively monitored with a single monitoring unit (Goldstein and Landovitz, 1977). The effective monitoring of urban air pollution can be done with a network of monitors. The monitors are located to meet optimally the monitoring objectives (Kanaroglou et al., 2005). Network objectives vary and are based on budgets that constrain the number of available monitors, the region's geography, the pollutant or pollutants of interest, and the pollutant characteristics. Examples of network objectives include detecting violations of a standard, monitoring the spatial and temporal variability, and measuring the effectiveness of abatement strategies (Lozano et al., 2009; Mazzeo and Venegas, 2007; Mofarrah and Husain, 2010; Nakamori and Sawaragi, 1984; Su et al., 2007).

Air pollution network design typically begins with the estimation of a set of expected air pollution concentrations for the study area (Kanaroglou et al., 2005; Su et al., 2007). These expected values are calculated by modelling air pollution emissions or from past monitoring results. The locations of the monitors are then chosen

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to meet the objective or multiple objectives of the network in an optimal way. This process, although robust, is usually unable to account for future changes in the air pollution field or monitoring network, which may include a reduced monitoring configuration, varying meteorological conditions, or changes in the type and location of the pollution source. Even with extensive planning most networks require periodic re-evaluation (Ainslie et al., 2009; Wu and Bocquet, 2011; Wu et al., 2010).

In this paper, we present a criticality index that is simple to implement and quantifies the importance of each monitor in the network. Currently, the approaches to evaluating monitors within an existing network are limited to the repurposing of techniques for locating entire networks, which are complex and challenging to implement (Ainslie et al., 2009). Our index defines the criticality of the monitoring units with historical data, spatial interpolation and simulations of reduced monitor configurations to determine the effect on spatial air pollution estimates. The index emphasizes the correct estimation of conditions above an air quality guideline, which are often set by the government of a region or through the adoption of global standards.

## 2. Methods

### *2.1. Study area and pollution monitoring data*

Our study area is located in Hamilton, Ontario, Canada's lower city, which is separated from the upper city by a 90-m escarpment and consists of industrial land use surrounded by residential property. The lower city is adjacent to Lake Ontario and over 60% of residents reported their air quality perception as fair or poor (Simone et al., 2012). Adams et al. (2012) have shown that land use changes in Hamilton have a significant effect on the spatial variation of air pollution concentrations. In Fig. 1, we present the study area, air pollution monitoring unit locations, and industrial lands. Mobile monitoring campaigns have identified that the highest concentrations of industrial related pollutants occur in this portion of the city (Kanaroglou et al., 2013). The other major source of air contaminants in Hamilton is vehicular emissions (Sahsuvaroglu et al., 2006). Hamilton is an important corridor connection between the Greater Toronto Area and the United States. Two major expressways traverse the city, which link to Buffalo, New York, and Detroit, Michigan, in the United States. The city has been growing with an increased suburban population that commutes to work and emits significant amounts of air contaminants (Adams et al., 2012).

The Hamilton Air Monitoring Network consists of 14 monitors with industrial partners financing 12 of them. The commitment of partners is not ensured, and the departure of one requires that the remaining parties fill the funding gap. This network that relies on private funding is a useful case study in identifying the criticality of each monitor because it may be necessary to assess the number of units that can be operated or maintained if any of the current partners decide to leave the group. Eight of the 14 stationary monitors measure particulate matter 10 μm or less in aerodynamic diameter ($PM_{10}$). The data used in this paper are a time-series of one-hour average concentrations beginning January 1st, 2011 and concluding on December 31st, 2011.

The Ontario Ministry of the Environment and Climate Change has set Ontario's $PM_{10}$ air quality standard (AQS) at 50 μg $m^{-3}$ averaged over a 24-h period (Standards Development Branch Ontario Ministry of the Environment, 2012). The hourly time-series data were transformed into 24-h moving averages, as shown below:

$$MA_h = \frac{c_h + c_{h-1} + c_{h-2} + \cdots + c_{h-23}}{24} \quad (1)$$

where $MA_h$ is the moving average of hour $_h$, and $c$ is the concentration obtained from the monitor for each hour.

### *2.2. Air pollution monitor criticality index*

The index quantifies each monitor's criticality to the system for reporting air quality conditions with an emphasis on introduced errors above the AQS. The index ($I$) is calculated for each monitor ($m$) in the network using a standardized cost function, which is

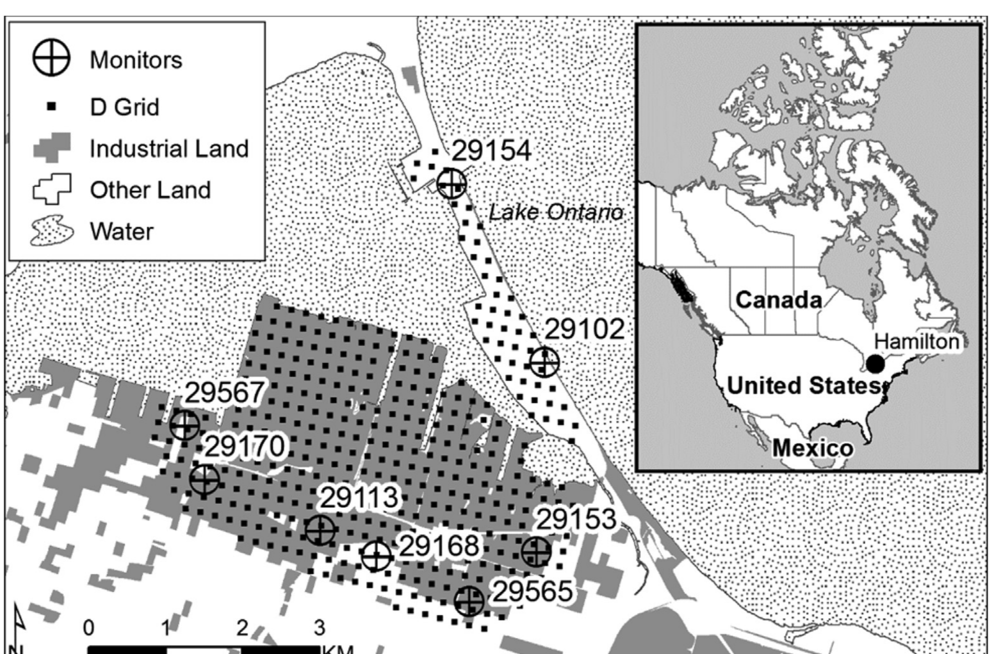


**Fig. 1.** Hamilton, Ontario study area, with the evaluation grid locations, industrial land use, and air pollution monitoring locations.