



Modeling the intraurban variation in nitrogen dioxide in urban areas in Kathmandu Valley, Nepal



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ABSTRACT

Background: With growing urbanization, traffic has become one of the main sources of air pollution in Nepal. Understanding the impact of air pollution on health requires estimation of exposure. Land use regression (LUR) modeling is widely used to investigate intraurban variation in air pollution for Western cities, but LUR models are relatively scarce in developing countries. In this study, we developed LUR models to characterize intraurban variation of nitrogen dioxide (NO₂) in urban areas of Kathmandu Valley, Nepal, one of the fastest urbanizing areas in South Asia.

Methods: Over the study area, 135 monitoring sites were selected using stratified random sampling based on building density and road density along with purposeful sampling. In 2014, four sampling campaigns were performed, one per season, for two weeks each. NO₂ was measured using duplicate Palmes tubes at 135 sites, with additional information on nitric oxide (NO), NO₂, and nitrogen oxide (NO_x) concentrations derived from Ogawa badges at 28 sites. Geographical variables (e.g., road network, land use, built area) were used as predictor variables in LUR modeling, considering buffers 25–400 m around each monitoring site.

Results: Annual average NO₂ by site ranged from 5.7 to 120 ppb for the study area, with higher concentrations in the Village Development Committees (VDCs) of Kathmandu and Lalitpur than in Kirtipur, Thimi, and Bhaktapur, and with variability present within each VDC. In the final LUR model, length of major road, built area, and industrial area were positively associated with NO₂ concentration while normalized difference vegetation index (NDVI) was negatively associated with NO₂ concentration ($R^2=0.51$). Cross-validation of the results confirmed the reliability of the model.

Conclusions: The combination of passive NO₂ sampling and LUR modeling techniques allowed for characterization of nitrogen dioxide patterns in a developing country setting, demonstrating spatial variability and high pollution levels.

1. Introduction

By 2008, over half of the world's population was living in urban areas, with more than 90% of urban population growth by 2030 occurring in developing countries (Obaid, 2007). The majority of the growth in the near future will occur in Asia and Africa, and Asia is predicted to contain more than half of the world's cities with population of 500,000 or more (Seto et al., 2010). High air pollution is one of the many environmental problems present in these urban areas. About 1.4 billion urban residents are currently living in areas exceeding World Health Organization (WHO) air quality guidelines (Zou et al., 2009), and according to WHO, about 3.7 million deaths in 2012 can be

attributed to outdoor air pollution worldwide (World Health Organization, 2014). Motor vehicles represent one of the main sources of pollution in urban areas (Health Effects Institute, 2011).

In spite of the increasing urbanization, high traffic volumes, and large health burden, exposure assessments are relatively scarce in developing countries (Han and Naeher, 2006). Studies specifically in developing nations are important as traffic-related air pollution is likely to differ between developing and developed nations due to differences in fuel characteristics, vehicle technology, contributions of heavy polluters (e.g., more motorcycles), driving habits, traffic patterns (e.g., frequent congestion) and roadways (e.g., graded vs. ungraded). In comparison to Western cities, Asian cities also have different built

Abbreviations: HB-HR, high building density and high road density; HB-LR, high building density and low road density; LB-HR, low building density and high road density; LB-LR, low building density and low road density; MPPW, Ministry of Physical Planning and Works; NDVI, normalized difference vegetation index; VDC, village development committee

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structure, topography, weather and land use patterns.

For traffic-related air pollutants, the within-city spatial contrast may be as large as the between-city contrast (Hoek et al., 2008), so traditional approaches such as assigning exposures based on values at the nearest monitors (Bell, 2006) are less interpretable. Land use regression (LUR) modeling has been widely used to investigate small scale variation in traffic-related air pollution (Poplawski et al., 2009), but to date, LUR models have been mostly limited to Europe and North America with only a few studies available in developing cities (Allen et al., 2013; Dionisio et al., 2010). In Asia, LUR studies have been in urban centers of China or other locales that may differ from rapidly urbanizing areas of South Asia (Allen et al., 2013; Chen et al., 2010; Kashima et al., 2009; Li et al., 2010).

High air pollution levels in the Kathmandu Valley of Nepal, one of the fastest urbanizing areas of South Asia, were first documented in the 1990s with pollution monitoring by several organizations, including the Kathmandu Valley Vehicular Emission Control Project funded by the United Nations Development Program and the Metropolitan Environment Improvement Project funded by the World Bank (International Center for Integrated Mountain Development, 2006). Vehicles were indicated as the main source of pollution by emission inventories developed in 1993 and 2001 (Asian Development Bank, 2006). Increasing number of vehicles, rapid and unplanned urbanization, population inflow, Valley-centric industrialization, poor road infrastructure, fuel adulteration and lack of regulations or enforcement of regulations contribute to the high air pollution present in the Valley. The Valley's bowl-like topography, low wind speeds limiting air pollution dispersion, and frequent thermal inversions also factor into the high levels of pollution. Despite the high air pollution, insight about health effects are limited by the dearth of air pollution data (Gurung and Bell, 2013), and very limited information is available on the spatial distribution of air pollution in the Valley.

In this study, we used LUR modeling to characterize intraurban variation of traffic-related air pollution in urban areas of Kathmandu Valley, Nepal. The methods were designed to address issues central to Nepal and similar countries, including limited data availability.

2. Materials and methods

2.1. Study area

The study area covers the urban core area of Kathmandu Valley, Nepal, consisting of the five urban village development committees (VDC). These five urban VDCs form Kathmandu Metropolitan City along with the surrounding municipal towns: Lalitpur, Bhaktapur, Kirtipur and Madhyapur-Thimi (Fig. 1). According to Population Census 2011, the urban area in the Valley constitutes 102 km² with population of 1,464,164. Annual average population growth in the past ten years was estimated at 4.32% for the Valley (Statistics, 2012). From 2000 to 2010 the number of registered vehicles in the Valley increased 274%, with 93% of the registered vehicles in 2010 being privately owned (Japan International Cooperation Agency, 2011).

2.2. Spatial allocation of sites

2.2.1. Site assignment region

We followed a strategy for site allocation that leveraged available geospatial data to try to maximize contrast among monitors and representativeness of measurements, as done in many previous studies in Europe and North America. A grid of 200 m×200 m was created over the five urban VDCs and each grid cell was assigned to a VDC. When a 200 m×200 m grid cell included the boundary of two or more VDCs, it was split into partial grid cells and a VDC was assigned to each partial grid cell. Similarly, at outer boundaries of the study area, a 200 m×200 m grid cell is partially within and partially outside the study area. Below we refer to complete cells of 40,000 m² (i.e.,

200 m×200 m) as 'full grid cells' and cells with area less than 40,000 m² (i.e., cells split by VDC boundaries or at outer boundaries of study area) as 'partial grid cells'. We refer to all cells (full grid cell and partial grid cells) as 'grid cells'. Input data (e.g., land use, road network) for LUR modeling are unavailable outside the study area or five urban VDCs. Before site allocation, a buffer of 400 m was created at the edge of the study area and going inward from the boundary of the study area to make sure that required input data for LUR modeling are available. We refer to 'site assignment region' as the study area after removing the area in the 400 m buffer at the boundary.

2.2.2. Assigning strata based on built density and road density

Detailed road networks and housing footprint (i.e., location and horizontal dimensions of buildings) data were obtained from the Ministry of Physical Planning and Works (MPPW), Nepal. Next for each grid cell in the site assignment region, building density and road density were calculated. 'Building density' refers to the fraction of built area within a given grid cell where 'built area' refers to the area of the building footprint. Supplement 1 shows the built area for the study area. 'Road density' refers to the density of roads within a given grid cell. Building density was divided into two categories within each VDC: the upper quartile (high building density) and lower three quartiles (low building density). Road density was similarly divided into two categories. By cross-classifying cells, four strata were created: high building density and high road density (HB-HR); high building density and low road density (HB-LR); low building density and high road density (LB-HR); low building density and low road density (LB-LR). Related approaches have been used in earlier studies (e.g., Matte et al., 2013).

2.2.3. Stratified random sampling

Based on the percent area covered within the study area by each of the five urban VDCs, 100 sites were distributed and additional sites added to ensure that each VDC had a minimum of 16 sites leading to a total of 114 monitoring sites. 114 monitoring sites were distributed with almost equal number of sites assigned to each of the four strata of building and road density within a given VDC (Supplement 2). Only grid cells from the site assignment region with area > 20,000 m² were eligible for site selection. Next, area-weighted random sampling was performed without replacement to select grid cells for monitoring sites. Using the area-weighted method, those grid cells with smaller areas (i.e., partial grid cells) had lower probability of being selected in comparison to those with larger areas. When a grid cell was selected, its neighboring grid cells were excluded from subsequent sampling. In Bhaktapur VDC, which has a small number of total grid cells, excluding neighboring grid cells of selected grid cells caused 4 sites (1 HB-LR cell, 3 LB-HR cells) to be added outside of the site assignment region or the study area after removing the area in the 400 m buffer at the boundary.

2.2.4. Purposeful sampling

After placement of 114 monitoring sites using stratified random sampling, an additional 21 sites were distributed in the study area. These 21 sites were allocated at least 300 m from the stratified random sampling sites already selected. Of the purposeful sites, 12 were allocated to major road intersections in the study area. The remaining 9 sites were placed to meet the following ranked criteria below (in the order performed): reduce major geographical gaps, cover regions with high population density, assign monitors in areas of concern, and spatially cover different land use types.

2.2.5. Field site identification

For each of the 135 sampling sites, suitable mounting structures were identified as close to the center of the grid cell as possible. When a grid cell selected for sampling was located in an inaccessible area, the nearest neighboring grid cell with the same stratum of building density and road density was sampled.

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