ABSTRACT

Title of Document: INFLUENCE OF WEEKDAYS, WEEKENDS, BANDHAS AND WEATHER CONDITIONS ON PARTICULATE MATTER (PM_{10}) CONCENTRATIONS IN THE KATHMANDU VALLEY IN NEPAL

Michelle Julia Fransen, Master of Public Health, 2011

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Particulate matter (PM) exposure has been associated with a variety of adverse health effects. Quantifying the relative source contribution of PM is important as it provides policymakers critical information needed to formulate successful pollution reduction programs. The aim of this study was to evaluate the effects of bandhas (general strikes) and meteorological parameters on PM_{10} concentrations in the Kathmandu Valley. Within station seasonal differences in PM_{10} concentrations were compared using t-tests. Linear mixed effects regression models were used to examine the effects of weekends or bandh days on PM_{10} concentrations. Results showed significant ($p<0.001$) seasonal variability across all stations. In the urban high traffic (UHT) and urban residential (UR) areas, there were statistically significant ($p<0.05$) lower PM_{10} concentrations on weekends. In the UHT, PM_{10} concentrations were significantly lower on bandh days ($p<0.05$). These results suggest that a reduction in vehicular emissions may alleviate the PM_{10} pollution problem in the valley.

INFLUENCE OF WEEKDAYS, WEEKENDS, BANDHAS AND WEATHER CONDITIONS ON PARTICULATE MATTER (PM_{10}) CONCENTRATIONS IN THE KATHMANDU VALLEY IN NEPAL

By

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Dedication

For my grandmother, Julia Graf, who inspired me to enjoy health. She will forever be the wind beneath my wings.

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Chapter 1: Introduction

Why is particulate matter exposure a public health concern?

Earliest records of air pollution date back to 61 AD when Roman philosopher Seneca wrote of the heavy air of Rome. Historically, air pollution was recognized as a nuisance, instead of a harmful agent with a potential to adversely affect human health in countless ways. However, a number of intense pollution episodes observed across completely unrelated parts of the industrialized world in the middle of the 20th century served as a wakeup call about the detrimental consequence of extreme air pollution. Between December 1 and 5, 1930, the largely industrialized area in the Meuse Valley of Belgium became covered in a thick fog, killing more than 60 people over the next three days (Nemery et al. 2001). Likewise, in 1948, the “killer fog” in the small town of Donora, Pennsylvania, killed 50 people and in 1952, the dangerous London “fog” devastated the population of the city with 4,000 deaths (Helfand et al. 2001; Scott 1953). Since then, public health professionals have paid close attention to the adverse health effects from air pollution (Dockery and Pope 1994).These studies have shown that long-term exposure to high levels of particulate air pollution, particularly PM_{10}, is associated with several adverse health outcomes, such as cardiovascular and respiratory diseases, and death (Dockery and Pope 1994; Samet et al. 2000). Other studies have shown exposure to increased levels of PM_{10} to be associated with low birth weight (Shah and Balkhair 2011), preterm delivery (Parker et al. 2008; Woodruff et al. 2003), decreased sperm motility (Selevan et al. 2000), asthma exacerbations (Dockery and Pope 1994), cardiovascular diseases (Bae et al. 2010; Diez Roux et al. 2008), lung cancer mortality (Pope III et al. 2002) and reduced lung function (Dockery and Pope 1994).

Children, adults with existing cardiovascular or respiratory problems and people living in the EPA's "nonattainment areas" are especially at risk to adverse health outcomes from exposure to high levels of particulate matter. Older adults may be at risk because of an undiagnosed heart or lung disease, but not at risk merely due to their age (EPA 2003). Children are at particular risk for adverse health outcomes following high amounts of PM_{10} exposure due to their immature immune systems and lung function and greater epithelial permeability to xenobiotics. Children also have a higher breathing rate than adults. This, included with their greater lung surface area per body weight and more time spent playing outside, can make them more susceptible to PM related adverse health outcomes (Schwartz 2004). In adults with existing heart disease, exposure to PM_{10} may cause chest pain, palpitations, arrhythmias, shortness of breath and fatigue. Increased coughing, wheezing, chest discomfort and medication use may occur in adults with lung diseases such as asthma or bronchitis (EPA 2003). Furthermore, people who live in PM_{10} "non attainment" areas, i.e. areas designated by the EPA to have failed to meet the national ambient air quality standards (NAAQS) for PM_{10}, are at risk since they are exposed to increased levels of air pollution on a regular basis, regardless of their existing health status (Paris et al 1993).

In order to protect the health of their people, many countries have adopted air pollution reduction programs and NAAQS. Although overall air quality has improved in many industrialized nations, unusually high levels of air pollution still plague many urban areas, particularly in developing countries. The rapid movement of rural population into the urban areas in search of better life has given rise to mega cities, where the pollution levels are much higher. Nepal is one of these countries that have persistent high levels of air pollution, especially in the capital area of Kathmandu Valley. Political instability combined with the lack of security and jobs in the rural areas has seen the population in the capital city of Kathmandu increase by nearly 50% percent within the past 10 years (Thapa et al. 2008). Additionally, there are no coherent regulations in place to control the emissions from the numerous automobiles and industries that are present in Kathmandu Valley (Joshi 2003). Dust resuspension from the poor road quality, tire burning and the use of biofuels for cooking and heating add to the increase in particulate matter concentrations. Therefore, to prevent an increased number of poor air quality related illnesses, diseases and death, it is important to understand the sources of PM_{10} and what variables affect the PM_{10} concentrations in the valley in order to solve the inherent air pollution problem.

Primary objectives / study design

The objective of this thesis is to determine the influence of weekdays, weekends, bandhas (general strikes, usually in a political protest) and weather conditions on particulate matter (PM_{10}) concentrations in the Kathmandu Valley in Nepal. Studies have shown that vehicular emissions are a leading source of increased levels of ambient PM_{10} concentrations (Dongarra et al. 2010; Joshi 2003). Furthermore, the reduction of those emissions through natural interventions has resulted in an associated reduction in ambient PM_{10} levels (Peel, et al. 2010; Wang et al. 2009; Friedman et al. 2001). In the Kathmandu Valley, weekends and bandhas serve as a catalyst for a natural intervention study. Since vehicular emissions are the leading source of particulate air pollution in the valley (Pudasainee et al. 2010; Joshi 2003), the reduction of vehicular activity, and closure of industries producing air pollutants, should lower the daily PM_{10} levels. Using publicly accessible PM_{10} concentration data available from the Ministry of Population and Environment of Nepal, along with weather data retrieved from Weather Underground, this study will attempt to demonstrate that PM_{10} concentrations will be lower on weekends and bandh days compared to weekdays and non-bandh days in the valley. Since weather has a significant effect on PM_{10} levels (Aryal et al. 2008), the influence of rain, humidity, temperature and wind on PM_{10} will also be addressed. By identifying the variations of PM_{10} levels, this study can serve as a reference for future studies of overall health outcomes in Nepal and as background for future air pollution reduction programs.

Thesis outline

This thesis is divided into four distinct chapters. Chapter 1 provides an overall introduction and the primary objectives of the thesis itself. Chapter 2 provides a background on particulate matter and related adverse health outcomes, meteorological influences on particulate matter, previous studies using a natural intervention approach on PM_{10} research and a discussion on the Kathmandu Valley and similar geographical areas. Chapter 3 presents five years of air quality data and provides results in support of the thesis's purpose. Chapter 4 provides a summary of the thesis, recommendations for air quality control programs and overall conclusions on the topic of PM_{10} air pollution.

Chapter 2: Background

In Chapter 1, the reasons for public health concern from particulate matter exposure, the primary objectives for the thesis and the thesis outline were presented. This chapter will provide an in-depth analysis of particulate matter, meteorological and other factors that influence particulate matter concentrations, present studies using a natural experiment approach and review information on the study area of Kathmandu Valley in Nepal, as well as other geographically similar regions of the world.

Particulate Matter

In addition to three primary gasses, nitrogen, oxygen and argon, the earth's atmosphere is composed of varying concentrations of water molecules and carbon dioxide and an assortment of harmful pollutants such as ozone, carbon monoxide, nitrogen oxides, sulfur dioxide, lead and particulate matter (Dunbar 2010, EPA 2010). Particulate matter (PM) is one of the most persistent forms of air pollution throughout the world. According to the United States Environmental Protection Agency (USEPA), particulate matter is "the term for a mixture of solid particles and liquid droplets found in the air" (EPA 2010). Some of these particles can be seen with the naked eye, such as dust, dirt, smoke or soot, while others can be seen only with the aid of an electron microscope.

Particulate matter is classified into four categories based on aerodynamic diameter: ultrafine particles (UFP, <0.1µm), $PM_{2.5}$ (fine particles, <2.5 µm), $PM_{2.5\text{-}10}$ ("coarse" particles, 2.5-10 µm) and PM_{10} ("thoracic" particles, <10 µm) (EPA 2004). Particulate matter in each classification is typically composed of a mixture of metals and carbon (Costa 2003). The most common metals in PM are metals released from engine wear (e.g., zinc, copper and lead), metals native to the earth's crust (e.g., iron, sodium and magnesium) and metals released during oil and coal combustion (e.g., transition and heavy metals). Carbon layers within the particle itself create the bulk of the particulate matter structure. Other chemicals that can be found in particulate matter are gypsum, syngenite, quartz, cement, silicon sulfide, siliconferro alloy, calcium, ferrochromium alloy, ammonium sulfate and chloride, molybdenum-rich, potassium sulfate and dolomite (Xie et al. 2009).

Sources of particulate matter

There are two general sources of particulate matter: anthropogenic and natural. Anthropogenic, or man-made, sources can be stationary or mobile. Stationary sources of anthropogenic particulate matter may include oil refineries, power plants, industries and municipal incinerators (District 2010). In the context of Kathmandu Valley, additional sources may include cement factories, brick kilns, industries using boilers and refuse burning (Pudasainee et al. 2010), domestic cooking fuels (Joshi 2003) or coal burning during the winter months (Sham et al. 2010). Mobile sources include exhaust from on-road vehicles, such as busses, trucks, cars, autorickshaws and motorbikes; non-road vehicles, such as construction vehicles, mowers and other fuel powered gardening equipment, ships, aircraft and trains; and off-road vehicles, such as snowmobiles and all terrain vehicles.

One of the most common forms of anthropogenic particulate matter is diesel exhaust (District 2010). Diesel PM is a matrix of ultra fine carbon and a mixture of combustion-derived complex polycyclic and nitroaromatic compounds and trace metals.

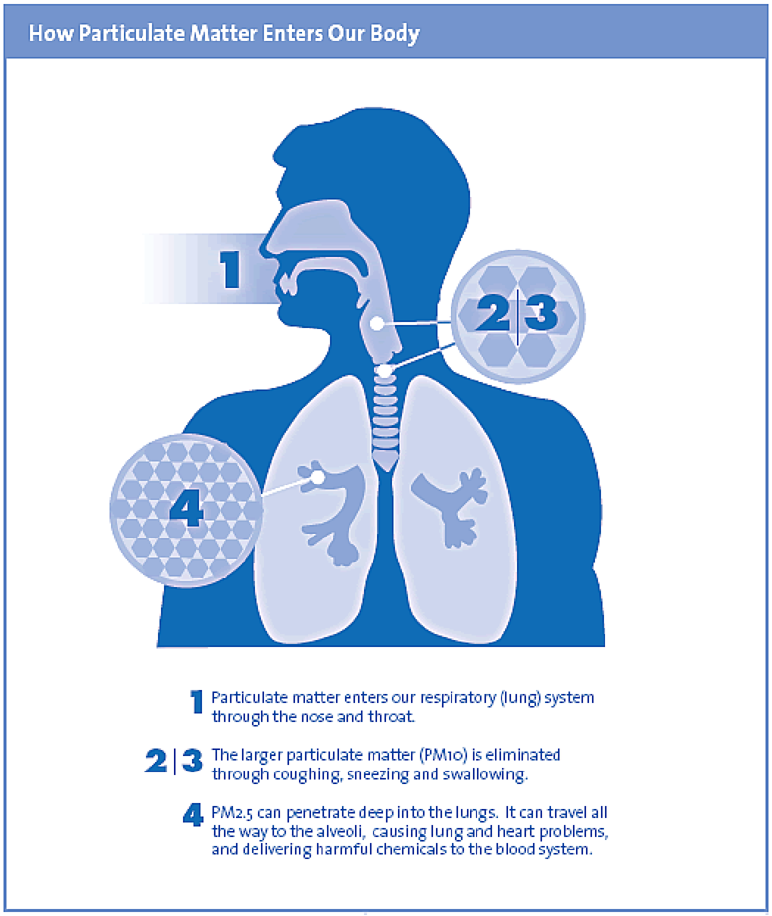
It also contains considerable amounts of inflammogenic and cytotoxic compounds, such as nitrous oxide, carbon monoxide, sulfur oxide, formaldehyde, acrolein and other aldehyde compounds (Costa 2003). Similarly, gas powered vehicles can also greatly contribute to the particulate matter air concentrations due to incomplete combustion (Collins and Scott 1993), poorly maintained vehicles on congested streets, poor quality fuels and lubricants, weaknesses in the emission inspection and maintenance system and a poorly managed public transportation system (Joshi 2003).

Natural sources of particulate matter can arise from geological or environmental disasters, such as forest fires or volcanoes. These sources are particularly troublesome since they cannot be prevented or controlled and have the potential to travel great distances. For example, in July, 2002, Quebec, Canada, experienced an increase in the number of forest fires. The effects of these fires were seen 1500 km away in Baltimore, Maryland. During the first weekend of July of the same year, Baltimore had a 30 percent increase in ambient fine PM, a direct result of the related Canadian forest fire (Sapkota et al. 2005). Similarly, the April 14, 2010, the eruption of the Eyjafjallajökul volcano in Iceland sent a tephra plume higher than eight kilometers into the air, spreading fluorine and silica rich ash over 1300km away to mainland Europe within the first 24 hours. In the next three days of the eruption, 70-80 million m^3 of magma was discharged, one of the largest eruptions on record. Eruptions continued for 10 days, cancelling, delaying and disrupting air traffic across the United Kingdom, Scandinavia and the rest of north western Europe for weeks (Sciences 2010).

How particulate matter enters the body

Inhalation through the mouth and nose is the most common route of human exposure to particulate matter (Costa 2003; Joshi 2003). Once inside the body, the site of deposition depends on the size of the particles. The larger particles, 50 microns (μm) or larger, are inhaled and deposited in the nasopharyngeal region as shown in Figure 1. Mucous covers the nasal surface and traps particles while the cilia move the insoluble material outwards to be removed by sneezing or by blowing and wiping the nose. Coarse particles deposit further down the trachea and into the bronchiolar regions of the lungs. Here, too, the mucous and cilia work to expel the PM out of the lungs via the mucociliary apparatus. The soluble matter is then either dissolved in the mucous or directly absorbed into the blood via the nasal epithalamium. The remaining solids, and the solids inhaled through the mouth, are swallowed and the associated toxins can be absorbed in the gastrointestinal tract. Conversely, fine and ultrafine particles are deposited directly in the alveolar regions of the lungs. Alveolar macrophages work to remove the toxins to be cleared by the lymphatic system (Rozman and Klaassen 2003). Those particles that are not removed from the lungs are absorbed into the blood (Terzano et al 2010).

Figure 1: How particulate matter enters our body. Copyright © Province of British Columbia. All rights reserved. Reprinted with permission of the Province of British Columbia. (Columbia 2010).



How Particulate Matter Enters Our Body

1 Particulate matter enters our respiratory (lung) system through the nose and throat.

2|3 The larger particulate matter (PM10) is eliminated through coughing, sneezing and swallowing.

4 PM2.5 can penetrate deep into the lungs. It can travel all the way to the alveoli, causing lung and heart problems, and delivering harmful chemicals to the blood system.

Although all sizes of particulate matter can be problematic when they remain in the body, the smaller sizes of particulate matter are more toxic due to their ability to get deeper into the lung tissue and remain there for a length of time (Costa 2003). Through coughing, the lungs are quite efficient at removing particles deposited in the trachea and the principle bronchus region. However, the removal of particles from the lower alveolar regions is much more difficult. In the first 24 hours, only 20 percent of the particles in the alveoli are actually cleared by the lymphatic tissue, phagocytosis or by the mucociliary escalator to the tracheobronchial region. After the first day, the remaining particles are removed very slowly. These rates of removal are proportional to the solubility of the compound (i.e., the lower the solubility, the slower the removal) (Rozman and Klaassen 2003). Ultimately, the longer the xenobiotic remains in the body, the higher the chances for an adverse health outcome.

Levels of particulate matter on health outcome

In 2005, the World Health Organization (WHO) set exposure guidelines for annual and daily PM_{10} exposures. While there is no threshold value for PM (i.e. the lowest level of exposure in which no adverse health effects are observed), the maximum annual daily mean exposure value (20 $\mu g/m^3$) and the maximum 24-hour mean exposure (50 $\mu g/m^3$) were set in order to minimize negative health outcomes associated with air pollution (Organization 2008). Country governments could choose to adopt these values as their own standards, or choose their own values. However, many countries lack enforced air pollution programs. A 2010 survey of national ambient air quality standards (NAAQS) of 96 countries showed that the average NAAQS for daily PM_{10} exposure was 95 $\mu g/m^3$ (95% confidence interval (CI): 82-108 $\mu g/m^3$), 90 percent higher than the published WHO NAAQS (Vahlsing and Smith 2011).

In the United States, the USEPA has set its own primary standard on maximum daily PM_{10} exposure at 150$\mu g/m^3$. However, this level should “not be exceeded more than once per year on average over 3 years” (EPA 2010). In other poorer or less developed countries who cannot afford to research their own NAAQSs, NAAQS from neighboring countries is typically adapted or adopted (Vahlsing and Smith 2011). This is the case for Nepal which adapted their NAAQS from their neighboring country of India.

The Government of Nepal has divided PM_{10} concentrations into corresponding air quality categories. The categories are defined as “Good” (0-60 $\mu g/m^3$), “Moderate” (61-120 $\mu g/m^3$), “Unhealthy” (121-350 $\mu g/m^3$), “Very Unhealthy” (351-425 $\mu g/m^3$) and “Hazardous” (>425 $\mu g/m^3$) (Giri et al. 2007).

Health implications from poor air quality

Since 1930, early studies in Meuse Valley, Belgium; Donora, Pennsylvania; and London, England; have related air pollution with adverse health outcomes, including mortality (Dockery and Pope 1994; Helfand et al. 2001; Scott 1953; Nemery et al. 2001). Symptoms of acute air pollution exposure can include itching or burning eyes, difficulty or impaired breathing with wheezing, coughing or aching lungs, headache and irritated nose and throat (Friis 2007). On the other hand, prolonged exposure to air pollution can have a negative effect on the cardiovascular and respiratory systems, the reproductive system (Dockery and Pope 1994; Selevan et al. 2000) and birth outcomes (Parker et al. 2008; Shah and Balkhair 2011; Woodruff et al. 2003) and may be associated with autism (Volk et al. 2010).

In 2000, a study was completed on the effects of air pollution and mortality in 20 urban areas in the United States over a seven year period. Results showed that there was a 0.51 percent increase in the relative rate of death for all causes and a 0.68 percent increase in the relative rate of death for cardiovascular and respiratory diseases for every increase of 10 $\mu g/m^3$ of PM_{10} (Samet et al. 2000). Similarly, by linking the American Cancer Society (ACS) cohort with air pollution data across the United States, Pope III et al., reported that a 10 $\mu g/m^3$ increase in fine particle PM was associated with a four, six and eight percent increased risk of all-cause, cardiopulmonary and lung cancer mortality, respectively (Pope III et al. 2002).

Exposure to particulate matter has also shown an increase in oxidative stress and the development of other cardiovascular ailments, such as atherosclerosis. Oxidative stress is the imbalance between the production and manifestation of reactive oxygen species and the body's reaction to detoxify free radicals or repair the resulting damage. This can lead to many diseases such as heart disease, myocardial infarctions and Parkinson's disease. In a study conducted in China and Korea, 120 children had statistically significant increases in urinary malondialdehyde (MDA) levels, a biomarker for oxidative stress, associated with increases in ambient PM levels (Bae et al. 2010). In a study of adults without diagnosed cardiovascular disease, results showed a 1 – 4 percent increase in their carotid intima-media thickness per 21 $\mu g/m^3$ increase in PM_{10} exposure (Diez Roux et al. 2008). This thickness is directly associated with the development of atherosclerosis.

Much like cardiovascular disease and particulate matter exposure, the effects of particulate matter and the respiratory system have also been studied. In one study, asthmatics had a three percent increase in attacks and bronchodilator use per 10 $\mu g/m^3$ increase in daily PM_{10} exposure. Additionally, they had a 3.4 percent increase in emergency department visits and a 1.9 percent increase in hospital admissions per 10 $\mu g/m^3$ increase in daily mean PM_{10} exposure (Dockery and Pope 1994). Otherwise healthy individuals also had a three percent increase in lower respiratory symptoms, such as wheezing, dry cough, phlegm or shortness of breath, and a 0.7 percent increase in upper respiratory symptoms consisting of stuffy or runny nose, sore throat, wet cough, head cold or burning and itchy eyes per 10 $\mu g/m^3$ increase in daily mean PM_{10} exposure (Dockery and Pope 1994).

The cardiovascular and respiratory systems are not the only parts of the human that can be affected by chronic exposure to particulate matter. A 2000 study showed that Czech men who were exposed to seasonal air pollution showed a decrease of motile sperm and an increase of sperm with abnormal chromatin, morphology and head shape when compared to non exposed controls (Selevan et al. 2000). Sperm count and concentration were not affected. In women, studies have been conducted on pregnancy and birth outcomes in those who are exposed to chronic particulate matter. Some studies showed there is a small increase in the odds of a preterm delivery (adjusted odds ratio = 1.05; 95% CI: 0.99-1.12) with women who live in a country with high levels of air pollution when compared to women living in countries with less air pollution (Woodruff et al. 2003).However, studies comparing birth weight and particulate matter exposures are inconclusive. Some studies showed that mothers exposed to high levels of particulate matter gave birth to babies who were small for their gestational age (Shah and Balkhair 2011) whereas others showed no change in regards to term birth weight (Gehring et al. 2011).

Autism and increased air pollution may also be related. In 2010, a study was conducted on pregnant women and children with autism living near a freeway. After adjusting for socioeconomic status, maternal smoking and maternal residence at the time of delivery, the odds of having an autistic child were 1.86 times (95% CI: 1.04-3.45) higher than that of living further away from a freeway (Volk et al. 2010). Although PM_{10}

and other air pollutants were not measured in this study, PM_{10} concentrations are higher closer to freeways compared to areas further away from freeways.

Meteorological influence on particulate matter concentration

Weather can have a strong influence on air pollution. Although rainfall and humidity are most strongly associated with lowered amounts of air pollution (Mok and Hoi 2005), temperature changes can also be responsible for additional air pollution variations (Giri et al.2008). In mountainous terrain, temperature inversions can act like a cap above the valley and hold the pollution inside. Typically, air becomes colder as the altitude increases, but during an inversion, the temperatures become warmer. This phenomenon occurs when cold air flows down the mountains and meets the warmer air rising from the valley stopping any atmospheric mixing, especially at night (Collins and Scott 1993).

Wind also affects air pollution in three ways. The first is due to anticyclonic weather systems. This large, slow moving air circulation around a high pressure system is associated with the removal of air pollution from a high concentration zone before the front, the accumulation of air pollution in the central isobaric pressure field and the movement of air pollution concentrations from the warmer, rear section of the system (Wei et al. 2011). Second, wind speed is inversely associated with air pollution concentrations in a given area (i.e. the faster the wind is blowing, the lower the concentration of air pollution) (Sivaramasundaram and Muthusubramanian 2009). Finally, wind can transfer air pollution over great distances, often affecting the air quality of an area thousands of kilometers away from the initial source of contamination (Sapkota et al. 2005; Sciences 2010).

Studies using a natural experiment approach

A natural experiment provides unique opportunities to study sources of air pollution as well as the resulting health benefits that may come to fruition because of the reduced air pollution level. Below are four examples of natural interventions studies where the main source of anthropogenic pollution was removed (e. g. coal and vehicular traffic). The resulting particulate matter levels were then compared to levels both prior to and after the source reduction or shut down. In all of these studies, when the pollution source was removed or reduced, associated PM_{10} concentrations were reduced.

Dublin, Ireland

The first example of a natural intervention study occurred in Dublin, Ireland. Here, a study on the effects of air pollution and death rates was conducted after the ban of selling, marketing and distributing of bituminous coals in the city on September 1, 1990. Coal burning was the largest source of particulate air pollution in Dublin. When the coal was banned, a natural intervention study was created. To test air pollution within the city limits, data was collected for 72 months prior to and after the ban was implemented. During the ban, particulate pollution in the form of black smoke decreased over 60 percent (from 50.2 to 14.6 $\mu g/m^3$, $p<0.0001$) from pre-ban concentrations. After the researchers controlled for weather, respiratory epidemics and death rates in the rest of Ireland, results showed that non-trauma death rates decreased by 5.7 percent, respiratory deaths decreased by 15.5 percent and cardiovascular deaths decreased by 10.3 percent (Clancy et al. 2002).

Utah Valley, Utah

A second example of a natural intervention study occurred in the Utah Valley in Central Utah. From April 1985 to February 1988, particulate matter levels in the valley were compared to hospital admissions for respiratory ailments and preterm birth rates. During this time period, the main source of particulate air pollution, the Geneva Steel Mill, was shut down for 13 months due to a labor dispute. When the mill was in operation, it contributed to 47 to 80 percent of the total emissions in the valley. The winter PM_{10} levels exceeded the USEPA's maximum daily PM_{10} exposure of 150 $\mu g/m^3$ 13 times, with the highest daily concentration totaling 365 $\mu g/m^3$. Hospital admissions for children increased almost three-fold and adults increased by 44 percent during days exceeding 150 $\mu g/m^3$ PM_{10} levels (Pope 1989). When the mill was closed, winter PM_{10} concentrations decreased approximately 50 percent. Daily PM_{10} concentrations never exceeded 150$\mu g/m^3$. Hospital admissions decreased significantly (Pope 1989) and women who were pregnant during the closure period were significantly less likely to have a premature delivery (Parker et al. 2008). Once the mill reopened, winter PM_{10} concentrations, adult hospital admissions and the likelihood of premature births rose again. This time there were 10 days exceeding 150 $\mu g/m^3$, with the highest concentration totaling 223 $\mu g/m^3$ (Pope 1989).

Atlanta 1996 Summer Olympic Games

A third natural intervention study occurred in Atlanta, Georgia, during the 1996 Summer Olympic Games comparing vehicular traffic patterns with ambient PM_{10}

concentrations. The Games of the XXVI Olympiad were held from July 19 through August 4. During this time, morning rush hour traffic in downtown Atlanta was reduced by 20 percent and the surrounding areas showed a traffic reduction between 2 and 15 percent compared to the one month baseline measurement before the Games (Peel et al. 2010). Results showed that PM_{10} concentrations collected from Georgia Institute of Technology in downtown Atlanta were reduced from 37.6 $\mu g/m^3$ (±14.2 $\mu g/m^3$) to 31.2 $\mu g/m^3$ (±10.4 $\mu g/m^3$), but was not statistically significant (p=0.239). On the other hand, a similar study reported by Friedman et al., showed PM_{10} concentrations had a statistically significant decrease (36.7 to 30.8 $\mu g/m^3$, 16.1% decrease, p=0.01) when compared to PM_{10} concentrations before the games (Friedman et al. 2001). Friedman, et al., also showed a significant decrease in pediatric asthma acute care rates (RR=0.48; 95% CI: 0.44-0.86) during the study period compared to baseline (Friedman et al. 2001). Although Peel, et al. reported no significant decrease in pediatric asthma emergency department visits (RR=0.953; 95% CI: 0.650-1.399), the researchers found a decrease in pediatric upper respiratory infections (RR=0.779; 95% CI: 0.632-0.962), upper respiratory infections in all age groups (RR=0.863; 95% CI: 0.767-0.970) and for all pediatric respiratory emergency department visits combined (RR=0.798; 95%: 0.789-0.969) (Peel et al. 2010).

Beijing 2008 Summer Olympic Games

A fourth intervention study occurred during the summer of 2008 in Beijing, China. Since the XXIX Olympic Games were held in one of the world's most polluted cities, strict air pollution reduction efforts were set into motion. In order to improve the air quality for the two and a half weeks of competition, the Beijing government reduced

50 percent of the vehicular traffic by adopting an “even-odd license place system” in which half of the vehicles would operate on alternating days. Businesses converted from coal burning fuels sources to natural gas. Factories and construction projects were also shut down (Wang et al. 2009).

Researchers from Peking University and Oregon State University monitored particulate air pollution for the two weeks prior, two weeks during and four weeks following the Games. Their results showed that PM_{10} concentrations were significantly lowered by 35 percent (p=0.022) during the competition period. Interestingly, atmospheric conditions accounted for 40 percent of the total variation in PM_{10} whereas only16 percent of the total variation was from source control during this study period (Wang et al. 2009). These results imply that weather patterns have a larger effect on the pollution in Beijing than local source control, emphasizing the importance of controlling PM_{10} pollutants on a regional scale across East Asia.

Study Location - Kathmandu Valley, Nepal

Geography and culture

Nepal is one of the poorest and least developed countries in the world (CIA 2011). It is a rectangular-shaped country that is completely landlocked with China to the North and India to the east, south and west (Figure 2). Kathmandu, the capital and largest metropolitan city in Nepal, is located around 27°42’N latitude and 85°20’E longitude with an area of 50.67 square kilometers. Kathmandu and her two sister cities Patan (Lalitpur) and Bhakhtapur, are situated at 1350 meters above sea level in the bowl shaped

Kathmandu Valley in the Himalayans surrounded by four major mountains: Shivapuri, Phulchowki, Nagarjun and Chandragiri .

Figure 2: A) Nepal. Photo courtesy of Central Intelligence Agency (www.cia.gov)
B) Geography of Kathmandu Valley, Nepal. Photo courtesy of NASA via Central Intelligence Agency (www.cia.gov)

A)

B)

The history of the country dates back over 2300 years ago and has since been ruled by both hereditary premiers and constitutional monarchs. In 2006, after several weeks of protests, the monarchy was overthrown by the Maoists and the country's first president of the Federal Democratic Republic of Nepal was elected soon thereafter. Even in the midst of political turmoil, Kathmandu relies heavily on commerce and tourism as the staple for their economy. The main source of income for the rest of Nepal is agriculture. As the land became more difficult to farm, people began to move into the urban valley in search of a better way of life. By 2001, the population in the valley was 671, 846 with a population density of 13,225 people per square mile (Office 2011).

Nepal's land use is divided among transportation, residential, agriculture and industry. Of the approximately 1036 kilometers of roads, 31 percent are blacktopped, 16 percent are gravel, 26 percent are earthen and 27 percent are made from other materials. The largest airport in Nepal, Tribhuvan International Airport, is also located in this region. Fifty-three percent of the land use is dedicated to residential buildings whereas agriculture uses about 18 percent of the land and 11 percent is used by services. The remaining 18 percent is used by greenery, business, mixed use and others (Office 2011).

There are several natural and environmental hazards that plague the Kathmandu Valley, as well as the rest of Nepal. First, the intensity and duration of the monsoons in the summer months lead to severe thunderstorms, flooding and landslides. Conversely, long months of no rain in the winter months lead to drought and famine. Secondly, deforestation has occurred since there were no available substitutes for wood used for fuel and cooking. Furthermore, water contaminated with human and animal waste, agricultural runoff and industrial effluents help the spread of infectious diseases due to the low number of modern waste water collection and treatment facilities. Finally, vehicular emissions from private and public use contribute to the overall poor air quality of the area (CIA 2011). Because of these conditions, the median age and life expectancy for men and women is 20.2 / 64.6 and 22.1 / 67.0 years, respectively (CIA 2011).

Weather and air pollution

The temperatures in the Kathmandu Valley are fairly consistent. The average daily (high/low) temperature in the valley ranges from 29/13° C in the summer to 17/2° C in the winter. Over 1400 millimeters of rain falls each year. Rain occurs most frequently during the summer monsoon season, June, July and August, dropping between 200 – 375 millimeters of rain on average. On the other hand, the drier months of November and December bring a paltry 2 – 10 millimeters of rain (Vista 2011). Snow rarely falls in the valley. Humidity can range from 80 percent during the summer to less than 50 percent in the winter months. Wind in the valley typically blows southwesterly at speeds between 0.5 and 7.5 m/s (Pudasainee et al. 2010; Aryal et al. 2008).

There are two reasons why the Kathmandu Valley may be particularly vulnerable to air pollution. The first is due to the topography. Because of the bowl-like feature of the Kathmandu Valley, emissions from vehicular traffic on unpaved or crowded streets, industries, burning refuse or tires and urbanization can remain in the atmosphere since the mountains restrict wind movement to disperse the pollutants (Pudasainee et al. 2010). Additionally, temperature inversions can act like a cap above the valley and hold the pollution inside. Typically, air becomes colder as the altitude increases. However, during an inversion, the temperatures become warmer. An inversion occurs when cold air flows down the mountains into the warmer air rising from the valley stopping any atmospheric mixing (Collins and Scott 1993).

The second reason why the Kathmandu Valley may be particularly vulnerable to air pollution is due to the altitude of the valley itself. At 1300 meters of elevation, atmospheric pressure is reduced to 86 percent of the pressure at sea level. Although there are the same percentages of molecules in the air, including oxygen, the concentrations are lower per cubic meter of atmosphere. This reduction in oxygen can result in a reduction in the efficiency of fossil fuel combustion, and a higher amount of unburned hydrocarbons may be created (Collins and Scott 1993).

Description of weekdays, weekends and bandhas

All regions of Nepal do not share the same business hours. Some parts of the country observe the typical Monday through Friday weekday with a Saturday and Sunday weekend. In the Kathmandu Valley, however, government and business offices are open Monday through Friday, but banks and major shopping centers are also open on Sundays. On Saturdays, everything is closed except for local shops (Vista 2011). Therefore, a weekday is considered Sunday through Friday and a weekend is considered Saturday.

A *bandh* (plural form: bandhas) is the Nepali word for “closure”. A bandh, also known as a general strike, can be called by any organization usually in a protest resulting in the halt of transportation (motor vehicles and busses) and the closure of businesses and industries severely impacting the daily lives of the people living in the affected area. Occasionally, demonstrators burn tires to block roads or burn effigies to protest political leaders (Pudasainee et al. 2010). The bandhas used in this study are listed in Table 1.

Table 1. Bandhas in the Kathmandu Valley, January 2003 to February 2008

Bandh Number	Dates	Description of Bandh
1	4/23/2003	General strike
2	9/18-20/2003	General strike
3	12/27-28/2003	Restricted traffic into the city
4	1/1/2004	Torch rally and restricted transportation movement
5	1/2/2004	Closure of roads leading to the Valley
6	1/3/2004	General strike
7	8/17-23/2004	General strike
8	*2/05-11/2006*	*General strike*
9	4/05-25/2006	General strike / April revolution
10	8/2/2006	General strike / tire burning
11	10/25/2006	General strike / tire burning
12	12/19/2006	General strike
13	1/21/2007	General strike
14	2/15/2007	General strike
15	2/28/2007	General strike
16	03/19-20/2007	General strike
17	5/27/2007	General strike / tire burning
18	6/1/2007	General strike / tire burning
19	6/28/2007	General strike
20	7/13-14/2007	General strike
21	*9/3/2007*	*General strike*
22	*2/3/2008*	*General strike*
23	*2/13-18/2008*	*General strike*

italics = missing station data / not used in this study

Other areas of the world geographically similar to Kathmandu Valley

San Joaquin Valley, California, USA

The San Joaquin Valley is located in the central region of California. The 250 mile long Valley includes eight of California's most agricultural fertile counties ringed by the Sierra Nevada Mountains to the east and the Diablo and Coast mountain ranges to the west (District 2010; System 2001). The valley houses over three million residents, two million vehicles, a large military air station, traffic from two large highway systems and numerous agricultural facilities that send emissions into the air. Due to long, hot summers, cool, foggy winters and frequent temperature inversions, most of the pollutants are trapped in the bowl shaped valley.

Fortunately, organizations such as the San Joaquin Valley Air Pollution Control District (SJVAPCD) have spearheaded the pollution problem. SJVAPCD, along with the state of California, have implemented programs to reduce vehicle, lawn and garden, pleasure watercraft and consumer product emissions and promote bicycle transportation and alternative fuel sources. Since the organization's inception in 1991, PM_{10} concentrations in the eight District counties have declined, on average, over 36 percent (Nester 2011).

Mexico City, Mexico

Mexico City, Mexico, is located in the southern third of Mexico and is considered to be one of the most polluted cities in the world. The capital city lies at 2200 meters in elevation with a 3000m mountain range to the north and a 3400m mountain range to the south. Mexico City is plagued with a booming population (six million residents in 1950 to over 20 million residents as of 2010), industries and few natural resources. Vehicles emissions are the main source of air pollution, contributing as much as 80 percent to the poor air quality. In the early 1990s, most of the vehicles were 10 years old and had meager functioning emission controls. Narrow streets and high traffic volume further increase the emissions. Even new engines may only perform at 60 percent, due to the poor combustion efficiency at the high altitude of the city (Collins and Scott 1993).

Stationary sources also contribute to the overall poor air quality. Laundromats, tortilla factories, public baths, metal smelters, petroleum refineries and thermal electric plants contribute to ozone and particulate matter concentrations in the Mexico Valley. In the mid 1970s, particulate matter concentrations ranged from 100 to 450µg/m^3. In 1991, the inversion layer over the valley was analyzed. Results of the study showed the particulate matter was concentrated at over 60,000 particles per cubic centimeter and was a continuous layer over 400 meters thick. Below this layer, 10,000 particles per cubic centimeter were detected. The atmosphere above the layer showed limited signs of particulate matter further stating that the inversion layer collects particulate matter and prevents the air pollution from leaving the valley (Collins and Scott 1993).

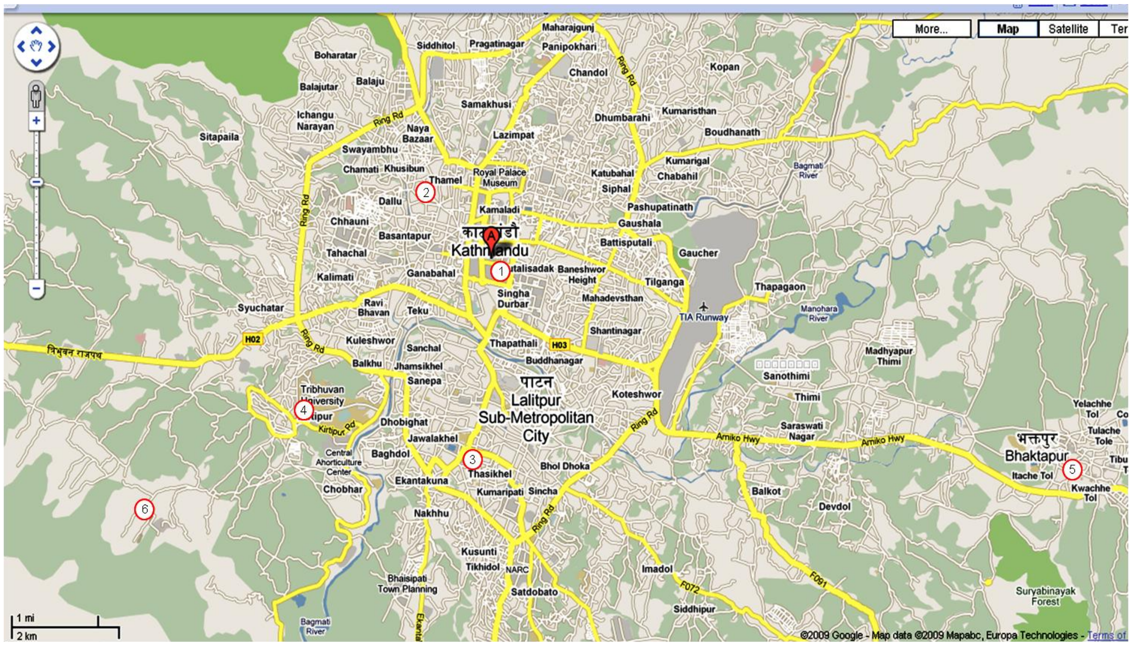
Chapter 3: Main Study

Material and methods

Sample Collection

Publically available PM_{10} concentrations were retrieved in 2008 from six air quality monitoring stations throughout the Kathmandu Valley from January 2003 – February 2008 via the Government of Nepal, Ministry of Population and Environment website: (www.mope.gov.np/mopepollution). These stations, shown in Figure 3, represent distinct areas in the valley: urban high traffic area (Putalisadak and Patan Hospital), urban residential area (Thamel), urban background (Bhakhtapur and Kirtipur) and rural village (Matsyagaon) (Giri et al. 2007). At each station, a Low Volume Sampler LVS for PM_{10} and $PM_{2.5}$ without pneumatic movement of filters (Model 85-02 of M/s. Instrumatic, Denmark) specifically designed for use in the Kathmandu Valley in the Kathmandu Air Quality Monitoring Program was used. The samplers' eight filters mounted three feet above the ground automatically collected 24 hour samples that were recorded daily as an average PM_{10} concentration in microgram per cubic meter ($\mu g/m^3$). Samples were collected once a week and analyzed by an approved laboratory (Giri et al. 2007). Weather data for the Kathmandu Valley were gathered from Weather Underground (www.wunderground.com) and dates for bandhas were found in the archives of *The Kathmandu Post* (www.ekantipur.com/tkp/), *Nepali Times* (www.nepalitimes.com/), *United We Blog! for a Democratic Nepal* (http://blog.com.np/) and *Nepal Bandha* (www.nepalbandha.com).

Figure 3: Map of air quality monitoring stations. Courtesy of Google.com



Note: 1 = Putalisadak. 2 = Thamel. 3 = Patan. 4 = Kirtipur. 5 = Bhakhtapur. 6 = Matsyagaon.

Statistical Analysis

All statistical analyses were performed using STATA 11.2 (College Station, TX). PM_{10} data were carefully checked for potential errors. If the PM_{10} concentration was less than 10 μg /m^3 or greater than 1000 μg/m^3, it was dropped from the final analysis as such extreme values were likely due to an error in data entry. The bandh dates and locations were cross checked with Google maps, to ensure the general strike occurred in the valley. Bandhas that occurred in Nepal, but not in the Kathmandu Valley, were excluded from this study, since the air quality in the valley would not be directly affected. Bandhas were arranged into 17 bandh periods, consisting of the PM_{10} concentrations for the average of two days before each bandh (i.e. “Before Bandh”), the day of the bandh (i.e. “Bandh”), the next three days immediately following the bandh day (i.e. “Bandh + 1”, “Bandh + 2”, "Bandh + 3", respectively) and the average of two days after each bandh (i.e. "After Bandh"). If a bandh lasted longer than one day, the average PM_{10} concentrations for all of the bandh days were included in "Bandh" and used in this analysis. To calculate percent change, "Before Bandh" PM_{10} concentrations were subtracted from "Bandh" PM_{10} concentrations and repeated with "Bandh + 1", "Bandh + 2", "Bandh + 3" to obtain "Diff 1", "Diff 2", "Diff 3" and "Diff 4", respectively. Paired t-tests were used to test statistical significances ($\alpha<0.05$) between winter and summer PM_{10} concentrations, weekend and weekday PM_{10} concentrations and "Before Bandh" and "Bandh", "Bandh + 1", "Bandh + 2" and "Bandh + 3" PM_{10} concentrations. A t-test was used to test statistical significances ($\alpha<0.05$) between the differences in percent change of PM_{10} concentrations from "Diff 1", "Diff 2", "Diff 3" and "Diff 4". Finally, linear mixed effects regression models were used to evaluate the relationship between weekday and weekend PM_{10} concentrations and "Before Bandh" PM_{10} concentrations to both "Bandh" and "After Bandh" PM_{10} concentrations. In the weekend and weekday model, the group variable was classified as a Monday to Sunday week with an unstructured covariance in order to randomize the effects of the weekend within each week. In the bandh model, the group variable was classified as the bandh id with an unstructured covariance in order to randomize the effects of the bandh within each bandh period.

Results and Discussion

Table 2 presents the main descriptive statistics of PM_{10} concentration variations by reporting station. The highest annual average concentrations of PM_{10} were observed in the urban high traffic areas of Patan and Putalisadak, with values ranging from 187µg/m^3

Table 2. PM_{10} Concentrations from Jan 1, 2003 to Feb 18, 2008 at the six Valley monitoring stations (in µg/m^3)

Station		Yearly	Winter	Spring	Summer	Fall
Putalisadak	Mean (SD)	216 (94)	291 (72)	266 (81)	142 (64)	169 (63)
	Median (p5-p95)	209 (81-379)	282 (190-415)	256 (163-419)	130 (64-267)	157 (80-294)
Thamel	Mean (SD)	135 (70)	202 (52)	160 (58)	71 (36)	100 (43)
	Median (p5-p95)	127 (45-260)	198 (126-291)	148 (87-274)	60 (37-134)	89 (45-182)
Patan	Mean (SD)	187 (74)	236 (58)	231 (69)	142 (59)	141 (45)
	Median (p5-p95)	182 (78-313)	228 (154-333)	225 (140-369)	130 (62-247)	140 (74-213)
Bhakhtapur	Mean (SD)	105 (72)	158 (64)	158 (65)	47 (34)	63 (28)
	Median (p5-p95)	91 (24-250)	140 (82-288)	144 (68-294)	35 (20-109)	57 (25-116)
Kirtipur	Mean (SD)	71 (44)	98 (33)	102 (42)	35 (28)	45 (21)
	Median (p5-p95)	66 (16-147)	93 (55.5-146)	96 (44-186)	25 (12-87)	41 (16-85)
Matsyagaon	Mean (SD)	49 (32)	60 (22)	74 (36)	31 (29)	31 (14)
	Median (p5-p95)	41 (14-112)	53 (30-100)	66 (28-138)	21 (11-81)	28 (13-58)

to 216µg/m^3, respectively. The lowest annual average concentration was observed for the rural village in Matsyagaon (49µg/m^3). The urban residential area of Thamel, and

Bhakhtapur and Kirtipur in the urban background had PM_{10} concentrations of 135µg/m^3, 105µg/m^3 and 71µg/m^3, respectively.

Days in each of the Nepal's NAAQS for are listed in Table 3. During the monitoring period, the Valley's air quality was classified as "unhealthy" or worse over 50 percent of the time. In other countries, such as the United States, the cut off for an "unhealthy" rating for PM_{10} exposure limit is 150µg/m^3. The days in the United States Environmental Protection Agency (USEPA) PM_{10} classifications are shown in Table 4. Overall, the unhealthy limits (>150µg/m^3) were exceeded over 1,019 times (70 percent) in Putalisadak and 915 times (65 percent) in Patan. The other stations had lower PM_{10} concentrations and reached 150µg/m^3 fewer times. Thamel, Bhakhtapur, Kirtipur and Matsyagaon exceeded 150 µg/m^3 585 (38.2 percent), 305 (23.2 percent), 65 (4.52 percent) and 16 (1.1 percent) times, respectively.

Table 3. Station days in each NAAQS (in µg / m^3) over the reporting period in the Kathmandu Valley

	Days	Percentage
Good (<60)	1,773	24.9%
Moderate (61-120)	1,723	24.2%
Unhealthy (121-350)	3,472	48.7%
Very Unhealthy (351-425)	124	1.7%
Hazardous (>425)	36	0.5%
Total station days	7,128	

Table 4. Days in each US EPA Air Quality Standards in (µg / m^3) over the reporting period

Station		G	M	USG	U	VU	H	Total
Putalisadak	Days	11	132	273	256	516	247	1435
	Percent	0.77	9.2	19.02	17.84	35.96	17.21	100
Thamel	Days	126	437	341	306	253	26	1489
	Percent	8.46	29.35	22.9	20.55	16.99	1.75	100
Patan	Days	10	159	327	364	504	89	1453
	Percent	0.69	10.94	22.51	25.04	34.69	6.13	100
Bhakhtapur	Days	373	347	290	147	139	19	1315
	Percent	28.4	26.39	22.05	11.18	10.57	1.44	100
Kirtipur	Days	546	546	280	48	16	1	1437
	Percent	38	38	19.49	3.33	1.11	0.07	100
Matsyagaon	Days	885	453	82	12	4	0	1436
	Percent	61.6	31.55	5.71	0.84	0.27	0	100

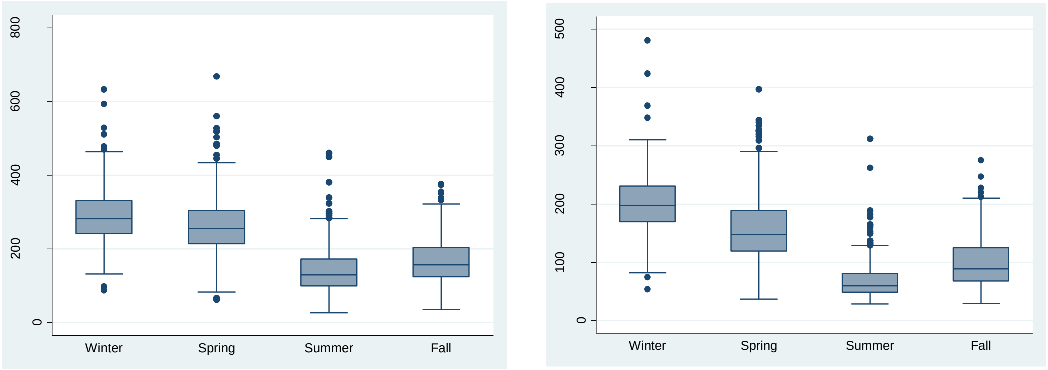
Note: Total days are not equal across stations due to omissions in reporting data. G = Good (<50), M = Moderate (51-100), USG = Unhealthy for sensitive groups (101-150), U = Unhealthy (151-200), VU = Very Unhealthy (201-300), H = Hazardous (>301)

These findings are comparable to previous studies. In 2008, Aryal, et.al, studied air pollution in the Kathmandu Valley between 2003 and 2007. They found higher annual levels of PM_{10} concentrations in the “busy traffic urban areas” followed by “urban residential areas" and "semi-urban areas" with the "rural area" having the lowest concentrations of PM_{10} (Aryal et al. 2008). These findings also suggest that the main sources of pollution in these industrial and high traffic areas are from industry and vehicular emissions (Giri et al. 2008; Dongarra et al. 2010). The rural area of Matsyagaon has lower ambient PM_{10} concentrations likely due to the lower influence of traffic and industry compared to the other stations.

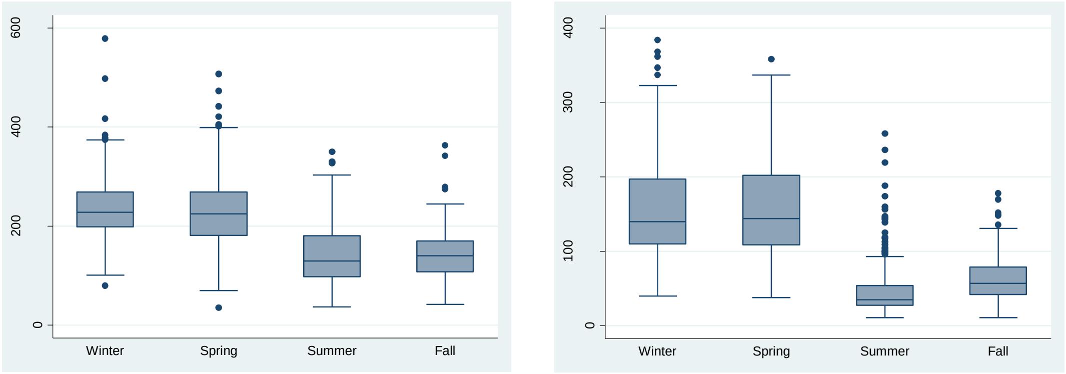
Seasonal and Weather Variation

Significant variability in PM_{10} concentrations was observed across different seasons (Figure 4). For this study, the months of December, January and February were considered the winter (dry) season. Spring (pre-monsoon) consisted of March, April and May. June, July and August were considered summer (monsoon) and September, October and November were considered fall (post-monsoon). The highest concentrations of PM_{10} were observed during winter in the urban high traffic areas of Putalisadak (290 ± 73µg/m^3) and Thamel (201 ± 52µg/m^3). In the rural area of Matsyagaon, the highest PM_{10} concentrations (74 ± 36µg/m^3) occurred in the spring. PM_{10} concentrations were relatively equally as high in winter (w) and spring (s) in the urban residential and urban background areas of Patan (w = 235 ± 58 µg/m^3; s = 231 ± 68 µg/m^3), Bhakhtapur (w = 157 ± 64 µg/m^3; s = 157 ± 65 µg/m^3) and Kirtipur (w = 97 ± 33 µg/m^3; s = 102 ± 42 µg/m^3). A paired t-test was performed to compare winter and summer mean PM_{10} concentrations. Across all of the monitoring stations in the summer season, there were statistically significant ($p<0.001$) lower PM_{10} concentrations than in the winter (Table 2).

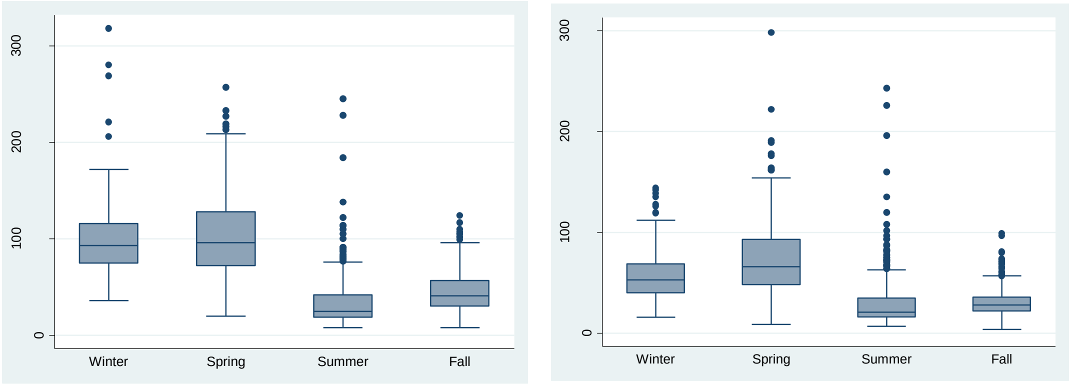
Figure 4. Seasonal variations among the six air quality monitoring stations in the Kathmandu Valley (in μg/m^3)



Putalisadak Thamel



Patan Bhakhtapur



Kirtipur Matsyagaon

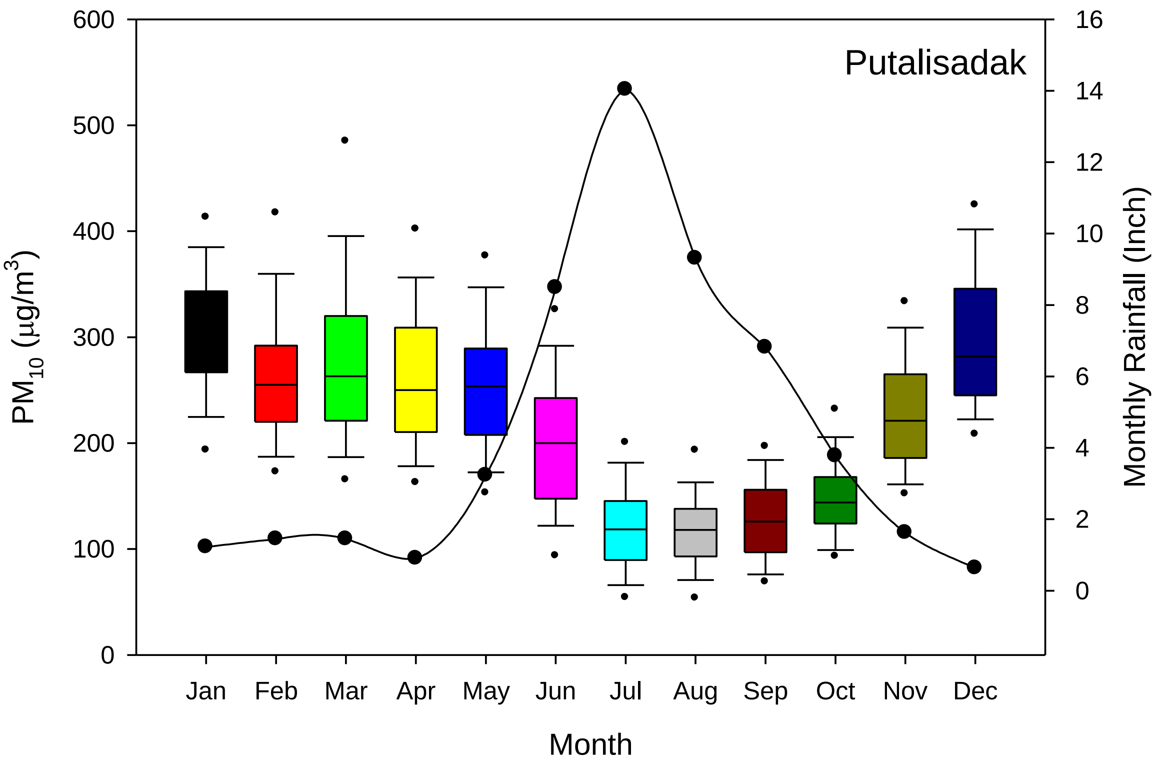
Note: Winter is December, January and February. Spring is March, April and May. Summer is June, July and August. Fall is September, October and November. Each box plot represents the median value in the middle of the box with 25th and 75th percentiles on the lower and upper ends. The ends of whiskers represent the 5th and 95th percentiles. Dots represent the outliers.

The effect of monsoon season on PM_{10} concentrations is depicted in Figure 5. With the arrival of monsoons in June, the amount of rainfall increases considerably, which also corresponds to declining PM_{10} levels. A linear regression analysis showed as the amount of average daily rain increases, the associated PM_{10} concentrations decrease ($\beta = -111.12$). Similarly, average daily temperature and humidity had statistically significant associations with PM_{10} concentrations ($\beta = -4.77$, $\beta = -3.43$, respectively). Average daily wind speed showed a decrease in PM_{10} concentrations, but was not significant ($\beta = -1.96$). (Data not shown. Simple linear regression model was used for the urban high traffic area of Putalisadak only. Similar seasonal weather associations are shown between the other monitoring sites in Aryal et al. 2008). Conversely, the winter months bring long periods of dry and cold weather. This coincided with the increased concentrations of PM_{10} concentrations across all monitoring stations. During the winter months, temperature inversions frequently occur resulting in entrapment of the pollutant within in the valley. This, combined with lack of washout associated with rainfall, more inefficient cold start emissions related to automobiles and the increased use of fossil or biofuels, may explain the increased PM_{10} concentrations observed during winter months.

It is interesting to note that PM_{10} concentrations are higher in the rural area of Matsyagaon in the spring and not in the winter as compared to the other monitoring stations. In addition to the lack of rainfall during the spring season as well, the higher levels of PM_{10} in Matsyagaon could be due to an increase in spring time agricultural activities, such as burning of agricultural waste for fertilizer, resuspension of dust from dry fields or an increase in pollen counts from flowering trees, grasses or other agricultural sources. Future studies are needed to analyze the differences in PM_{10}

composition in the urban areas versus the rural areas of the Kathmandu Valley in order to make this determination.

Figure 5: Concentrations of PM_{10} in Putalisadak (urban high traffic area) and rainfall, by month



Note: Each box plot represents the median value in the middle of the box with 25th and 75th percentiles on the lower and upper ends. The ends of whiskers represent the 5th and 95th percentiles. Dots represent the outliers.

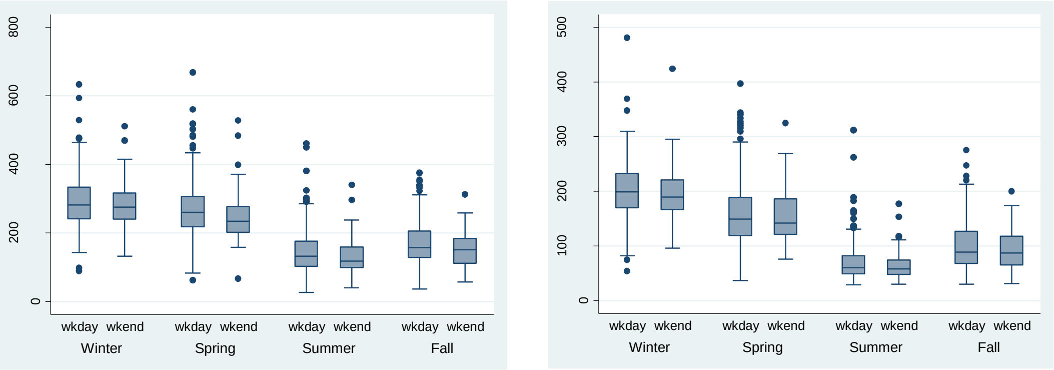
Weekend and Weekday Variation

Figure 6 shows the comparison of weekday (Sunday through Friday) and weekend (Saturday) PM_{10} concentrations for each of the six monitoring stations. Paired t-tests were used to compare weekend and weekday PM_{10} concentrations (Table 5). Weekends had statistically significant ($p \leq 0.05$) lower PM_{10} concentrations than weekdays in the urban high traffic areas of Putalisadak and Patan (217.5 ± 94.1 vs. 203.9 ± 93.3 $\mu g.m^3$, p =0.0184 and 189.0 ± 74.0 vs.172.5 ± 73.8 $\mu g.m^3$, p =0.0007, respectively).

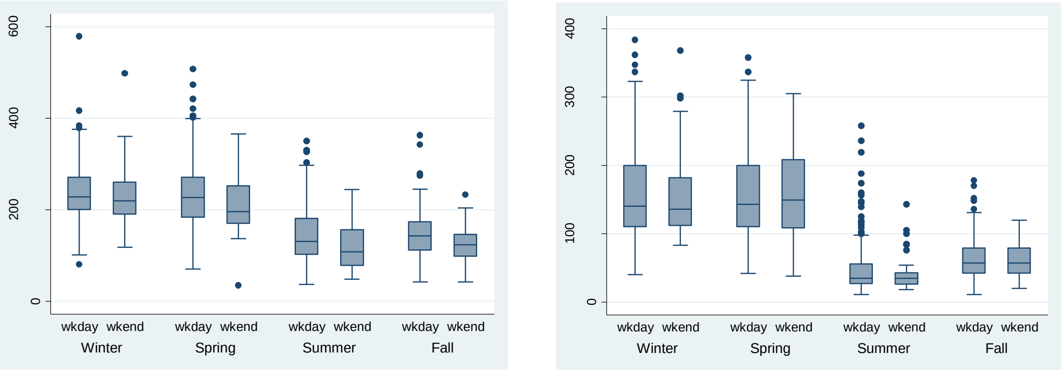
After controlling for seasonal differences (rain, wind, humidity and temperature), linear mixed effects regression models were then used to evaluate the relationship between weekdays and weekends by taking into account weekly correlations among PM_{10} concentrations (Table 6).The regression coefficients (β-value) for Putalisadak and Patan also showed a statistically significant negative association; lower weekend PM_{10} concentrations than those on a weekday ($\beta = -12.52$, p =0.005; $\beta = -16.41$, p <0.001,respectively). Additionally, the urban residential area of Thamel showed a statistically significant negative association; lower weekend PM_{10} concentrations than those on a weekday ($\beta = -5.77$, p =0.012).

The lower PM_{10} concentrations on the weekend in the high traffic areas of the Kathmandu Valley can be attributed to the lower volume of vehicular traffic driving on the roads since government agencies and large shopping centers are closed. Additionally, industries are not open on Saturdays in the Kathmandu Valley, further reducing the anthropogenic sources of PM_{10} pollution.

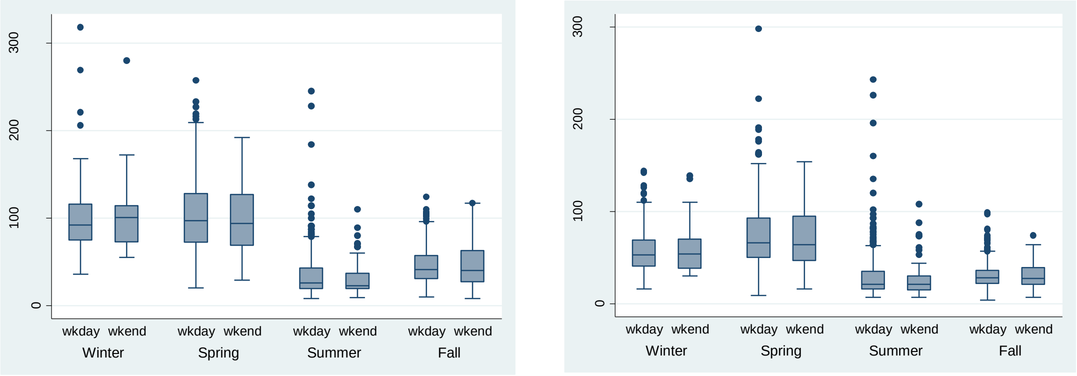
Figure 6. Weekday and weekend variations among the six air quality monitoring stations by season in the Kathmandu Valley (in µg/m^3)



Putalisadak Thamel



Patan Bhakhtapur



Kirtipur Matsyagaon

Note: A weekday is Sunday thru Friday. A weekend is Saturday. Winter is December, January and February. Spring is March, April and May. Summer is June, July and August. Fall is September, October and November. Each box plot represents the median value in the middle of the box with 25th and 75th percentiles on the lower and upper ends. The ends of whiskers represent the 5th and 95th percentiles. Dots represent the outliers.

Table 5. PM10 concentrations for Weekday, Weekend, Before Bandh, Bandh, Bandh + 1, Bandh + 2 and Bandh + 3 (in µg/m3)

	Mean and (SD)							P-values comparing:				
	Weekday	Weekend	Before bandh	Bandh	Bandh + 1	Bandh + 2	Bandh + 3	Weekday vs. Weekend	Before vs. Bandh	Before vs. Bandh + 1	Before vs. Bandh + 2	Before vs. Bandh + 3
Putalisadak	218 (94)	204 (93)	242 (23)	210 (24)	225 (22)	235 (25)	235 (24)	0.018	0.010	0.091	0.326	0.287
Thamel	136 (70)	132 (69)	135 (17)	132 (18)	139 (21)	143 (20)	138 (22)	0.202	0.174	0.461	0.764	0.612
Patan	189 (74)	173 (74)	168 (16)	148 (19)	158 (15)	160 (17)	155 (22)	0.001	0.111	0.265	0.518	0.204
Bhakhtapur	105 (72)	104 (72)	99 (20)	90 (20)	95 (18)	104 (17)	105 (20)	0.393	0.042	0.307	0.923	0.854
Kirtipur	71 (44)	72 (46)	64 (9)	64 (9)	61 (8)	62 (8)	65 (8)	0.550	0.667	0.364	0.323	0.614
Matsyagaon	49 (33)	48 (31)	51 (8)	49 (9)	48 (10)	53 (9)	48 (8)	0.392	0.256	0.290	0.764	0.230

Note: Weekday is Sun-Fri. Weekend is Sat. Before bandh PM_{10} concentrations are an average of the prior two days before the bandh day. If a bandh lasted for more than one day, the average PM_{10} concentrations on each of the bandh days were used.

Bandh Variation

Table 5 shows the PM_{10} concentrations on the average of the two days before bandh (“Before Bandh”), the day of the bandh (“Bandh”) and the next three days immediately following the bandh day (“Bandh + 1”, “Bandh + 2” and “Bandh + 3”, respectively). Paired t-tests were performed to test the statistical significance ($\alpha<0.05$) in the differences between PM_{10} concentrations. Although there was a reduction in PM_{10} concentrations in five of the six monitoring stations, the urban high traffic area of Putalisadak and urban background areas of Bhakhtapur showed statistically significant decreases in PM_{10} concentrations from “before bandh” to “bandh” (242.4 ± 23.2 vs. 209.9 ± 24.4 $\mu g/m^3$, $p=0.0096$; 99.4 ±19.9 vs. 90.2 ± 19.5 $\mu g/m^3$, $p=0.0417$, respectively).

Next, linear mixed effects regression models were used to examine the relationship between “Before Bandh”, “Bandh” and “After Bandh” by taking into account the correlations within each bandh period (Table 6). After controlling for seasonal differences (rain, wind, humidity and temperature), the regression coefficients (β-values) showed lowered PM_{10} concentrations across all monitoring stations, but Putalisadak (urban high traffic area) showed the only statistically significant ($p<0.05$) decrease from “Before Bandh” to “Bandh” days ($\beta= -38.33$, $p=0.042$). All monitoring stations also showed a decreasing pattern from “Before Bandh” to “After Bandh”, however, none of the stations showed statistically significant results.

Table 6. Mixed effects regression analysis comparing A) weekday to weekend and B) before bandh to bandh and after bandh PM_{10} concentrations

A) Weekday vs. Weekend

Station	β-value	*p*-value	95% CI
Putalisadak	-12.52	0.005	(-21.18 - -3.86)
Thamel	-5.77	0.012	(-10.29 - -1.24)
Patan	-16.41	0.000	(-24.46 - -8.36)
Bhakhtapur	-1.76	0.417	(-5.99 - 2.49)
Kirtipur	0.90	0.606	(-2.51 - 4.31)
Matsyagaon	-1.33	0.287	(-3.78 - 1.12)

B) Bandhas

	Before Bandh vs. Bandh			Before Bandh vs. After Bandh		
	β-value	*p*-value	95% CI	β-value	*p*-value	95% CI
Putalisadak	-38.33	0.042	(-75.31 - -1.34)	-27.92	0.075	(-58.68 - 2.83)
Thamel	-2.79	0.829	(-28.07 - 22.49)	-10.04	0.338	(-30.57 - -10.48)
Patan	-6.26	0.665	(-34.62 - 22.10)	-3.62	0.766	(-27.49 - 20.24)
Bhakhtapur	-9.59	0.376	(-30.82 - 11.64)	-5.71	0.518	(-23.03 - 11.60)
Kirtipur	-2.31	0.779	(-18.46 - 13.85)	-5.68	0.392	(-18.71 - 7.34)
Matsyagaon	-3.82	0.626	(-19.19 - 11.55)	-11.31	0.054	(-22.81 - 0.187)

Note: "Weekday" is Sun - Fri. "Weekend" is Sat. "Before Bandh" is the 2 day average before bandh. "After Bandh" is the 2 day average after bandh. "Bandh" is the day of bandh, or if the bandh is longer than 1 day, the average across all bandh days.

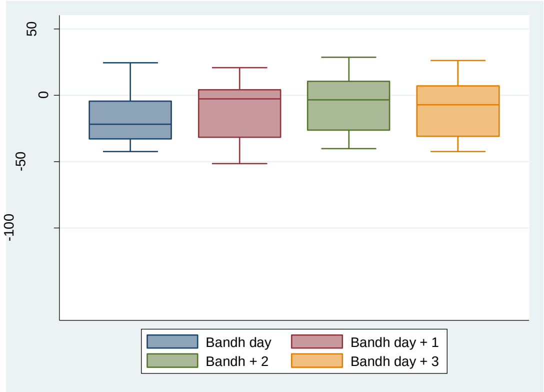
To minimize seasonal PM_{10} differences, a percent change calculation was performed by subtracting "Before Bandh" PM_{10} concentrations from "Bandh" PM_{10} concentrations and the calculation was repeated with "Bandh + 1", "Bandh + 2" and "Bandh + 3". These values are represented in Table 7 as "Diff 1", "Diff 2", "Diff 3" and "Diff 4", respectively. A t-test was performed to test the statistical significance ($\alpha<0.05$) for each percent change. Across all stations, PM_{10} concentrations were lowered by 7.3 to 27.2 percent on bandh days compared to the average of the two days prior to each bandh (Diff 1). Results were only statistically significant in the urban high traffic area of Putalisadak ($p=0.0212$) (Table 7). Additionally, all stations showed a smaller negative percent change with "Diff 2", but results were only significant in the rural village of Matsyagaon (-17%; $p=0.0427$). Putalisadak had a -10.7 percent change, just above the statistically significance level cutoff ($p=0.0548$). Figure 7 shows the relationship of the percent changes across all monitoring stations.

Table 7. Differences in PM_{10} concentrations between Before Bandh and Bandh, Bandh + 1, Bandh + 2 and Bandh + 3 (in percent change)

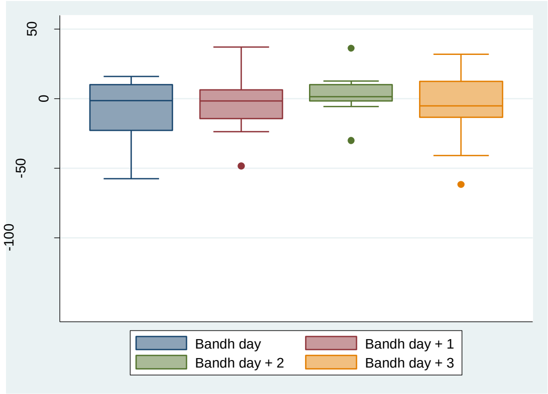
	Diff1		Diff 2		Diff 3		Diff 4	
	Mean (SD)	*p*-value	Mean (SD)	*p*-value	Mean (SD)	*p*-value	Mean (SD)	*p*-value
Putalisadak	-27.2 (12.2)	0.0212	-10.7 (6.1)	0.0548	-8.0 (6.5)	0.1219	-8.4 (6.5)	0.1111
Thamel	-7.3 (6.4)	0.0831	-3.6 (5.2)	0.1452	2.9 (3.7)	0.7725	-6.21 (6.4)	0.1740
Patan	-26.1 (18.7)	0.0981	-12.4 (14.4)	0.2195	-7.44 (6.7)	0.2963	-22.4 (14.8)	0.0801
Bhakhtapur	-14.8 (8.7)	0.0730	-3.4 (5.9)	0.3741	10.8 (4.8)	0.9765	7.2 (5.6)	0.8852
Kirtipur	-7.3 (9.6)	0.2685	-8.7 (9.1)	0.2153	-11.9 (12.4)	0.1777	-0.3 (7.9)	0.4869
Matsyagaon	-7.6 (6.2)	0.0944	-17.4 (8.5)	0.0427	0.6 (9.3)	0.5264	-10.5 (10.9)	0.1769

Note: Diff 1 = Bandh - Before Bandh. Diff 2 = Bandh + 1 - Before Bandh. Diff 3 = Bandh + 2 - Before Bandh. Diff 3 = Band + 3 - Before Bandh.

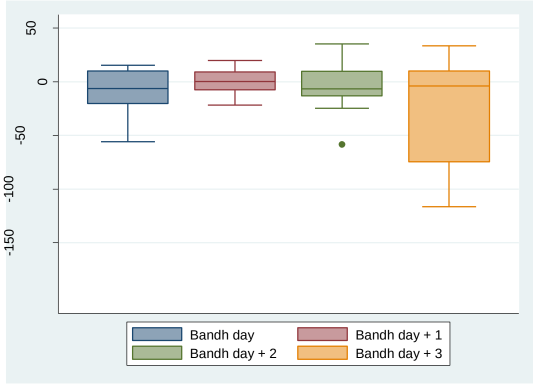
Figure 7: PM_{10} concentrations between bandh day, bandh day + 1, bandh day + 2 and bandh day + 3 compared to the average PM_{10} concentration on the two days prior to the bandh day (in percent change)



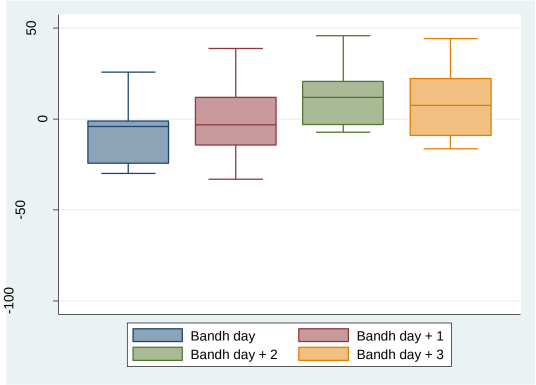
Putalisadak



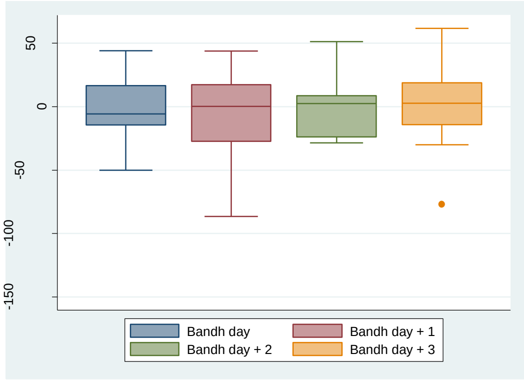
Thamel



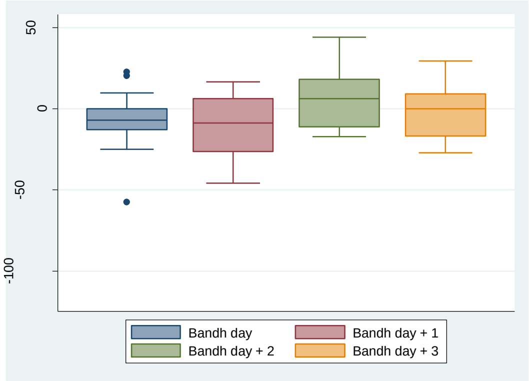
Patan



Bhakhtapur



Kirtipur



Matsyagaon

Note: Each box plot represents the median value in the middle of the box with 25th and 75th percentiles on the lower and upper ends. The ends of whiskers represent the 5th and 95th percentiles. Dots represent the outliers.

These results show that if the leading source of PM_{10} is reduced or removed; associated ambient PM_{10} concentrations can also be reduced. These findings are comparable to previous intervention studies. In Dublin, Ireland, particulate pollution in the form of black smoke decreased over 60 percent ($p<0.0001$) during the 1990-1996 ban on coal sales, marketing and distributing, compared to the six years before the ban (Clancy et al. 2002). Similarly in the Utah Valley in Central Utah, winter PM_{10} concentrations were nearly 50 percent lower when the Geneva Steel Mill near Orem, Utah was closed, compared to the previous winter (Pope III 1989).

Reductions in vehicular traffic during the 1996 and 2008 Summer Olympic Games in Atlanta and Beijing also showed lower PM_{10} concentrations during the Games, compared to PM_{10} concentrations before the Games (16% decrease, $p=0.01$ and 35% decrease, $p=0.022$, respectively) (Wang et al. 2009; Friedman et al. 2001).

Strengths and Limitations

The strengths of this present study discussed below. First, the monitoring locations were located throughout the Valley, reflecting different environmental settings of urban high traffic, urban residential, urban background and rural village. By comparing all reporting stations, a better understanding of PM_{10} concentrations from anthropogenic sources, and the variations of PM_{10} concentrations, can be further understood. Second, associations were made between bandh and non-bandh days by comparing of raw air quality data and percent change data to account for differences in seasons and atmospheric conditions. Finally, to the knowledge of the researchers, this is the first study to look at ambient PM_{10} variations comparing weekdays to weekends and bandh days to non-bandh days over a five year period as a natural intervention experiment.

This study also had some limitations. First, due to the complete closures and restricted traffic movement during bandhas, there appeared to be difficulty in reporting air quality samples during bandh days. Of the 65 days of observed bandhas, 21 days were missing air quality data completely and 26 were missing observations from one or more monitoring stations. If air quality data had been complete before, during and after each bandh day, this analysis could have had an increase in statistical power and therefore may have shown a stronger association between bandh and non-bandh days in regards to differences in PM_{10} concentrations across all stations.

Second, pinpointing exactly when and where the bandhas occurred proved to be difficult. Bandh dates had to be retrieved from numerous sources such as websites, newspaper articles and blogs, but there may be sources of error in the reporting dates as there was not one resource that listed all bandhas in the valley. (In future studies, www.nepalbandha.com will be a valuable resource for bandh dates and data, but the site only began bandh reporting in 2007, the last year of this study period.)

Third, there was no set matrix on how extreme the bandhas may have been. Some bandhas last a few hours, therefore only briefly restricting traffic, whereas other bandhas may last days or weeks. Additionally, during some bandhas, protestors may conduct torch rallies or block traffic from driving on roads by burning tires in intersections. These emissions from torches and burning tires include carbon monoxide, sulfur and nitrous oxides, volatile organic compounds and particulate matter (NCDENR 2000), that may cause an increase in air pollution on bandh days. It is also not known exactly where in the valley the protesting may have occurred. By knowing how extreme the each of the bandhas was, a stronger statistical analysis could have been achieved.

Finally, this present study only addresses reductions in ambient PM_{10} concentrations during weekends and bandhas, not personal PM_{10} exposures. Weekends and bandhas may not be associated with personal PM_{10} exposures, or they may be higher than the ambient outdoor PM_{10} concentrations during weekends and bandhas. Both of these cases may lead to a higher overall exposure to PM_{10} (Scapellato et al. 2009). It is important to address additional personal exposures from indoor air pollution, such as smoking or burning fossil and biofuels for cooking and heating in unventilated areas of their homes, when investigating reductions in PM_{10} concentrations and adverse health outcomes.

Conclusion

In conclusion, this study analyzed the influence of weekdays, weekends, bandhas and weather on particulate matter (PM_{10}) concentrations in the Kathmandu Valley in Nepal. The results showed significantly high PM_{10} concentrations throughout the valley, especially in the urban high traffic areas of Putalisadak and Patan. The results also showed statistically significant seasonal PM_{10} variations across all six monitoring stations. Furthermore, there were statistically significant lower PM_{10} concentrations on weekends in the urban high traffic and urban residential areas and bandhas in the urban high traffic areas strongly suggesting that vehicular emissions are a leading source of PM_{10} air pollution in the valley.

Chapter 4: Summary, Programming and Overall Conclusions

Summary

Vehicular emissions are leading sources of air pollution from particulate matter in the Kathmandu Valley (Pudasainee et al. 2010; Joshi 2003; Dongarra et al. 2010). This thesis successfully showed that when vehicular emissions are decreased, there is an associated decrease in PM_{10} concentrations, especially in urban areas plagued by high volumes of traffic. By having a decrease in the PM_{10} concentrations throughout the valley, this study suggests that cardiovascular, respiratory and reproductive health should improve, as well as morbidity associated with exposures to increased concentrations of PM_{10}. This research can be used in future studies in order to make correlations between adverse health outcomes on people residing in the Kathmandu Valley for medical treatments for asthma, respiratory illnesses, cardiovascular ailments, or for other hospital visits such as pregnancy, labor and delivery or postnatal care for infants, or as a background for air quality improvement programs.

Air Quality Improvement Program

Since 2004, the Clean Air Network Nepal (CANN) has been working to improve the air pollution problem in the Kathmandu Valley and in the rest of the country (Manandhar and Thapa Magar 2010). Government agencies such as the Ministry of Environment, Science and Technology, Ministry of Transport, Ministry of Industry and other organizations within the Clean Air Initiative-Asia (CAI-A) and Clean Energy Nepal networks have developed programs focusing on air quality management (CEN 2011). Although this program has not discussed their evaluation protocols, or results from their evaluation studies, a linear regression model was used with this thesis's data set to evaluate the yearly PM_{10} concentrations in Putalisadak, the urban high traffic area, before and after the program's inception. After controlling for rain, temperature, wind and humidity there was a statistically significant ($p<0.05$) increase of PM_{10} between the years 2003-2007 (2007 was the last full year of the data set) (β-value = 11.68, $p<0.001$). However, since there is no air quality data from the valley after February, 2008, it is not safe to assume that this program is not efficient.

In order to supplement the CANN program's initiatives for improving air quality for the residents of Kathmandu and the surrounding areas, the activities below are geared towards reaching the following three objectives:

1. Reduce leading causes of air pollution by 50 percent in five years and 75 percent in ten years
2. Reinstate and maintain the Kathmandu Valley's six air quality monitoring stations
3. Promote use of infrastructure

Each of these activities will be managed by a local worker and data relating to the efficiency and success of each activity will be collected and analyzed. These reports will be submitted quarterly to the program manager and reported to the funding agency bi-annually.

Activities

In reference to the first objective, to reduce leading causes of air pollution by 50% in five years and 75% in 10 years, I am proposing five different activities. The first activity is to impose stricter vehicular emission standards and regulation. Many of the valley's vehicles are older and poorly maintained (Joshi 2003). The unavailability of quality fuels and oils contribute to the PM_{10} pollution problem due to the incomplete combustion of carbon at the valley's higher altitudes (Collins and Scott 1993). Auto mechanics should receive training on proper maintenance procedures and yearly emissions testing should be completed on every vehicle older than five years. These regulations should apply to all personal vehicles, motorbikes, public transportation busses and government vehicles such as police cars and ambulances. Availability to quality automotive fuel sources should also be improved. Additionally, there should be an improved access to the use of electric vehicles. This is a continuation of Nepal's Clean Air Campaign from 2004-2005 promoting clean vehicles (CEN 2011).

A second activity is to improve the surface of dirt and other non-blacktop or cement roads. Dirt and gravel roads lead to an increase in dust resuspension once vehicles, motorbikes, walkers or other travel over the roads. If the surface is harder, there will be less dust available to contribute to ambient PM_{10} concentrations. In the mean time, an improvement of pedestrian and bike paths will make it safer for both to navigate through the downtown and rural areas. Also, if these paths are promoted as an alternate to vehicular traffic, there should be a decrease of vehicles actually driving on the roads. Furthermore, areas of high pedestrian traffic should be off limits to vehicles. One of the successes of the CANN was that the Durbar Square in Kathmandu was declared a "no-vehicle" area in 2010 (CEN 2011). This resulted in a safer and healthier area in one of the highest tourist and commercial areas in downtown Kathmandu.

A third activity is to improve industry emissions. Even though the largest industrial polluter (Himal Cement Factory) was shut down a decade ago, brick kilns continue to contribute a large portion of PM_{10} to the air pollution problem (Joshi 2003).

The kilns' smoke stacks should be fitted with filters such as the Smoke Stack Exhaust System (U.S. Patent 5145498). This filter uses water to scrub gasses in order to remove particulate waste. The washed gasses are vented to the atmosphere and remaining water solutions are passed through a series of filters, thus reducing toxic chemicals and particles from the emissions (Houston 1992).

A fourth activity is to evaluate and supply alternative, eco-friendly sources of cooking and heating fuels. Refuse and biomass are currently used as sources for cooking and heating (Joshi 2003). If accessibility to alternate sources of fuels such as liquid petroleum (LP) or kerosene, PM_{10} concentrations could also be reduced. Not only could the use of these natural fuels lower ambient PM_{10}, but levels of indoor air pollution could also be lowered.

Finally, a fifth activity is to improve the populations' air pollution awareness and education on actions to reduce their pollution footprint. The CANN already has a multitude of webinars, seminars, weekly radio programs, interactive school programs and symposiums geared towards clean air initiatives (CANN 2011). Groups should also be organized in order to plant trees, bushes and grass to help with erosion and dust aerosolization and to help naturally clean the air. Consideration should be given to planting the *Ficus benghalensis* (Banyan) or *Mangifera indica* (Mango) tree. Although the Banyan tree has a higher leaf surface area, waxier coating and longer life span than the Mango tree, the leaves of both trees have been shown to have a high level of magnetization and have a natural ability to capture more particulates from road sources (Prajapati and Tripathi 2008).

The second objective is to reinstate and maintain the Valley's six air quality monitoring stations. These stations were constructed in 2002 with assistance from the Danish Government (Rai 2010). They were located around the valley in four distinct areas: two urban high traffic areas, one urban residential area, two urban background areas and one rural village. By 2008, the stations had fallen into disrepair and the monitoring program was cancelled. A report from The Kathmandu Post states that "there seems to be no interest in operating the stations to monitor the visible rise in air pollution inside the Valley" (Rai 2010). In order to evaluate any air quality improvement program, the valley's air quality needs to be monitored itself. In my opinion, the reinstatement of the monitoring systems, especially in the urban high traffic and urban residential areas, are very important to the success of any air pollution reduction program. The proposed activity will have the monitoring stations managed jointly by the Ministry of the Environment and Ministry of Health and Population. Since this and other studies have stated that the highest concentrations of PM_{10} are in the urban high traffic and residential areas, these areas will be the first to exhibit reductions of PM_{10} concentrations.

The final objective is to promote the use of infrastructure. The first activity to support this objective is to ensure local authorities, safety officials and environmental agencies enforce the guidelines of this, and other, air quality improvement programs. Those found in violation should be reported and fined. Fines should be split between the local authorities, auto mechanics tasked with improving vehicle emissions and programming funds to develop a working economic relationship. Furthermore, joint work with Nepal, China and India to reduce air pollution as a whole (Clean Air Initiative for Asian Cities) should be conducted on a regular basis. Based on a study conducted in

Beijing, China, after the 2008 Olympic Games, researchers discovered that after a reduction in vehicular traffic, 40 percent of the source pollution in Beijing between August 2 and 24, 2008, came from areas outside of the region. Additional studies show that particulate material can travel great distances, leading to increased concentrations of PM_{10} over 1500km away from the source (Sapkota et al. 2005). These results show that if different countries work together on reducing air pollution, air quality could be improved within the entire region.

Concluding Thoughts

In conclusion, people all over the world are exposed to PM_{10} air pollution. In most areas, daily PM_{10} exposures are low. However, in urban areas where vehicular and industrial emissions are high, especially those cities located in valleys, PM_{10} exposures can be much higher. Those who are regularly exposed to higher levels of PM_{10} can suffer from a number of adverse health outcomes more frequently than those who are not exposed to the same concentrations of PM_{10} (Dockery and Pope 1994; Samet et al. 2000; Selevan et al. 2000; Pope III et al. 2002; Woodruff et al. 2003; Diez Roux et al. 2008; Bae et al. 2010; Shah and Balkhair 2011) This thesis has shown that seasons and meteorological systems have a significant influence on variations of PM_{10} concentrations. Furthermore, when the predominant sources of PM_{10} pollution are removed or reduced, associated levels of ambient PM_{10} are also reduced.

In developing countries, such as Nepal, it is especially important for air quality programs be developed, managed, supported and evaluated in order to reduce ambient PM_{10} pollution. It is hopeful that the results of this study are used in future studies of associated health outcomes and will serve as a catalyst for future air quality reduction programs.

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