April 2014

GIS Analysis of Factors Influencing Particulate Pollution in Keene, New Hampshire

Sean K. Spendley
Keene State College, kinjiro89@gmail.com

Christopher E. Brehme
Keene State College, cbrehme@keene.edu

Follow this and additional works at: http://commons.pacificu.edu/ijurca

GIS Analysis of Factors Influencing Particulate Pollution in Keene, New Hampshire

Peer Review

This work has undergone a double-blind review by a minimum of two faculty members from institutions of higher learning from around the world. The faculty reviewers have expertise in disciplines closely related to those represented by this work. If possible, the work was also reviewed by undergraduates in collaboration with the faculty reviewers.

Abstract

This study aims to identify the characteristics of air inversions and Particulate Matter 2.5 ($PM_{2.5}$) in the city of Keene, New Hampshire. $PM_{2.5}$ is a type of particulate pollutant with a diameter of less than 2.5 microns that exists naturally, and can be created through industrial processed and the combustion of biomass. The combustion of wood as a home heating fuel is considered the main source of $PM_{2.5}$ in Keene. Meteorological factors were investigated by searching through quality assured meteorological record provided by the New Hampshire Department of Environmental Services. Wintertime temperature inversions are of particular concern as they trap pollutants near the ground, creating high concentrations of $PM_{2.5}$. This is particularly true for Keene, which is in a glacial valley. This study concluded that air inversions and high $PM_{2.5}$ event are most likely to occur on cold, clear, windless nights during the winter. The temperature must drop at least 11 degrees Fahrenheit, with a dew point close to the ambient temperature. The other objective of the study was to create a model that would predict the areas that will experience high $PM_{2.5}$ concentrations as the result of demographic and topographical factors. The model was built using Digital Elevation Models, and building footprints provided by the University of New Hampshire Database. Housing density was calculated using the building footprints layer, and combined with areas that have less than three degrees of slope. This was compared to mobile monitoring data collected during the timeframe of the study.

Keywords
GIS, PM 2.5, temperature inversions, woodsmoke, air quality

Editor's Note: Dr. Christopher Brehme, Assistant Professor, Department of Geography, Keene State College, served as faculty mentor for this work.

INTRODUCTION

Exposure to airborne pollutants can have various negative health effects, so their study is tantamount to maintain a healthy populace. Particulate Matter 2.5, or PM2.5, is a specific type of particulate pollutant consisting of particles that are less than 2.5 micrometers in diameter, and can be comprised of chemically active and inert components. Long and short term elevation of PM levels has been linked to increased respiratory issues, morbidity, and mortality (Janssen et al. 2013). This increase occurs for both cause-specific mortality and general mortality. PM2.5 is the result of combustion of biomass, coal, and other fossil fuels. Various studies have explored the health effects of this form of particulate pollution. Janssen et al. (2013) showed that the majority of particulate air pollution consists of PM2.5, in some cases up to 60%. The authors showed that there was an immediate increase in mortality in urban areas in the Netherlands given high PM2.5 levels. Particularly susceptible populations include infants, young children, the elderly, and those with existing health problems (Haley, Talbot and Fenton 2009; Janssen et al. 2013; Gavett and Koren 2001). Most evidence shows that the majority of deaths associated with PM2.5 events are due to heart failure and in subjects with existing cardiovascular conditions (Haley, Talbot and Fenton 2009; Janssen et al. 2013). Older adults are susceptible to both conditions, but young adults are also affected. Studies conducted in areas of high PM2.5 levels showed that the pollutant causes increased heart rate variability in seemingly healthy young adults, which is a widely used predictor for future hypertension and heart disease (Vallejo et al. 2006).

Asthma and respiratory issues have also increasingly been associated with PM pollution. Genetic predisposition for asthma could not account for the dramatic rise in the number of those afflicted in the last few decades, and scientists hypothesized that PM was a factor. Gavett and Koren (2001) found a strong relationship between high PM levels and asthmatic response in lab mice, most likely stemming from high concentrations of transition metals in PM2.5. PM2.5 has also been linked to lung damage, as it causes high concentrations of destructive oxidizing chemical species. This damage necessitates constant cellular autophagy and reproduction, reducing the lung's ability to transfer oxygen to the bloodstream (Deng et al. 2013).

Keene, New Hampshire has experienced ongoing problems with PM2.5. Considering the clusters of families with children, and presence of several nursing homes in Keene, it is important to determine the sources and locations of the pollutant. The city of approximately 23,000 sits within a glacially carved valley approximately 480 feet above sea level, with a flat floor that slopes to the south. It is surrounded by hills that range from 700 to 1200 feet above sea level, which influence the mixing of air within the valley. It is hypothesized that the biggest influence on PM2.5 concentration is wintertime temperature inversions. Inversions are short term meteorological events that occur when one air mass is overlain by another of substantially different

temperature and density, and the normal temperature gradient is flipped. This means that a warm layer of air sits on top of a cold layer of air. This stratification is very stable and very effective at preventing the exchange of air between strata, which can greatly reduce the dispersion and transport of air pollution (Baumbach and Vogt 2003). Wintertime air inversions occur close to the ground and are usually the result of heat sources such as cars and houses, sunlight on paved roads, and the release of latent heat during dew and frost fall (Whiteman, De Wekker, and Haiden 2007). Local topography can aid in the creation of inversions, when cold air slides downhill underneath the warm air from the urban heat island. Inversions in Keene commonly occur on clear windless nights, when air temperatures are very cold.

While Keene lacks the meteorological monitoring devices to reliably determine the presence of air inversions, the most extreme PM2.5 events generally coincide with predictions of the phenomenon. Anecdotally, a haze of low lying wood smoke with a distinct upper limit is often visible on such days. The visible boundary is a telltale sign of an air inversion. It therefore seems to be a relevant factor in the study of PM2.5 concentrations in the area, and the characteristics have been considered in the creation of the model. Additionally, wood smoke was considered the primary source of the particulate matter. Keene lacks the industry and major transportation routes that exacerbate particulate pollution in larger urban areas. The Keene Air Quality Working Group, a collection of academic and government researchers and local

planners, has identified the use of wood as a heating fuel to be a primary source of particulate pollution in the area.

The aim of this study is to determine the conditions that cause a PM2.5 event. This involves research into the weather patterns preceding and during the events in Keene, as well as an analysis of local relief. We hypothesize that both climactic and topographic factors play a role in PM2.5 concentration.

DATA

Meteorological Factors

Quality assured meteorological records were obtained from the New Hampshire Department of Environmental Services (NHDES) in tabular form. These data consist of hourly readings from the monitoring station in downtown Keene from October 1st 2012 through March 29th 2013. Each entry has records of temperature in Fahrenheit, wind direction, wind speed, and PM2.5 concentration. We also utilize the weather history from NOAA, which provides additional data like precipitation, relative humidity, barometric pressure, as well as more frequent climate readings than the NHDES data.

We were provided a set of mobile monitoring data gathered by Dr. Nora Traviss of Keene State College and her students on December 3rd 2012, and January 8th 2013. This was collected at ten second intervals along a large looping path using a Thermo Scientific pDR-1500, as dictated by the conditions of a research grant provided by the NHDES. The equipment
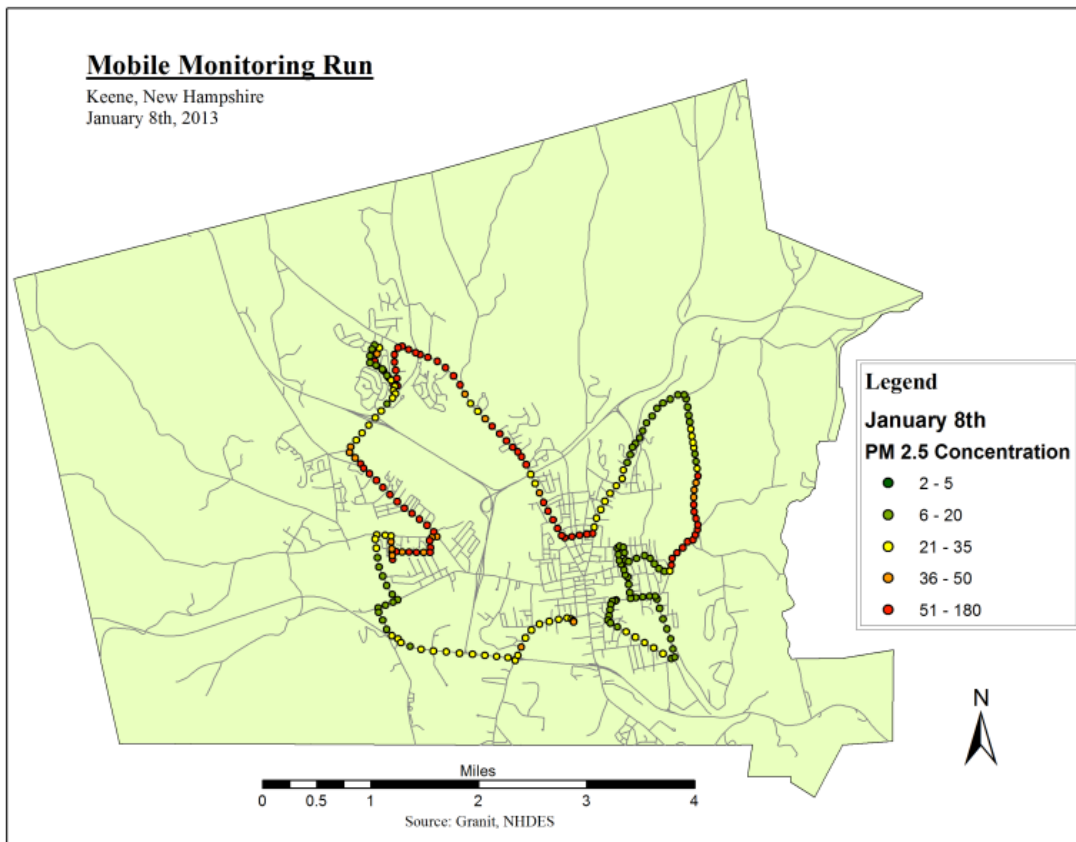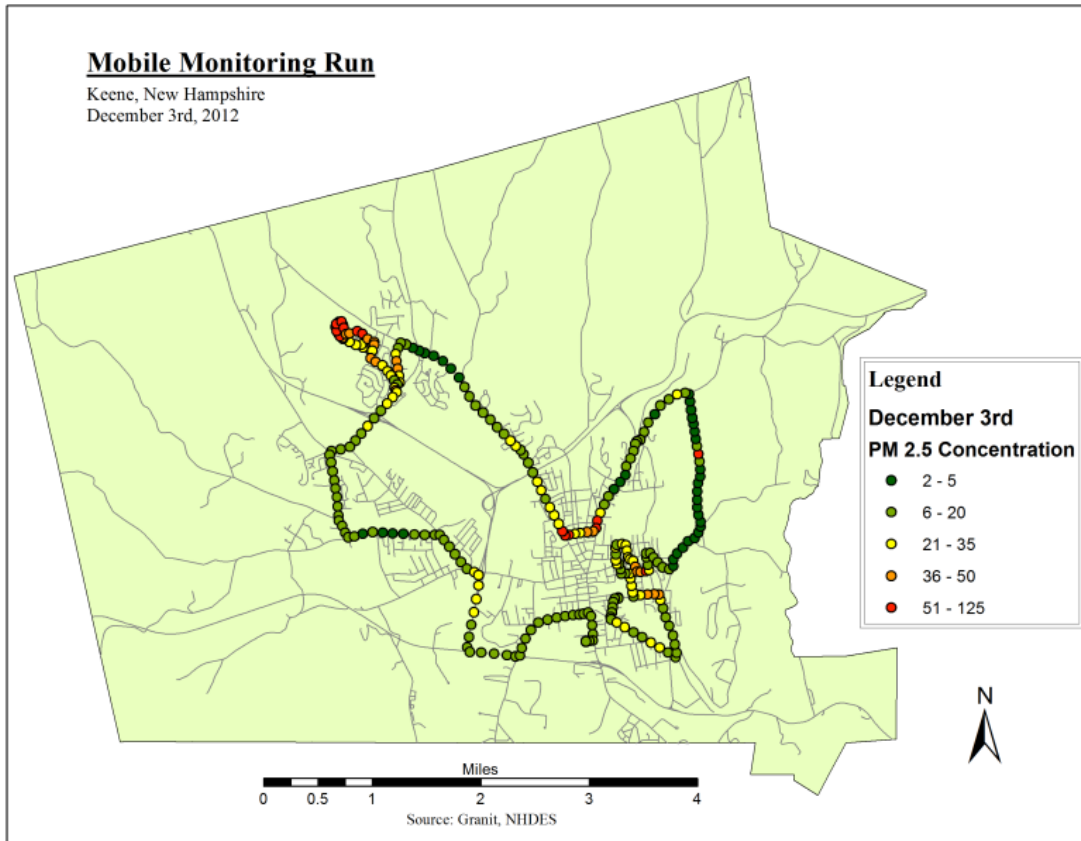
Figure 1. Mobile monitoring collection runs from December 3rd, 2012, and January 8th, 2013.

was installed on a frame in the rear seat of a car, and the sensor extended above the car through an otherwise sealed window. Each point is geo-tagged using a GPS, which was monitored by a student in the rear seat.

Modeling

This study makes use of the data available from the United States Geological Survey (USGS) and the University of New Hampshire's Geographically Referenced Analysis and Information Transfer System (GRANIT) GIS database. These consist of a Digital Elevation Model (DEM) from the National Elevation Dataset (NED) as provided by the USGS. GIS layers from GRANIT of the local roads and town boundaries are used to provide locational context for the mobile data readings, and a shapefile of building footprints is used to calculate rudimentary housing density.

METHODS

Meteorological Factors

Determining the weather at the time of PM2.5 events required the examination of weather archives. First, the monitoring station data provided by the NHDES was used to identify the days in which PM25 concentrations were above the 35µg/m3 daily limit, as dictated by the Environmental Protection Agency. The EPA determined that a 24 hour rolling average of 35µg/m3 was the upper limit of exposure before an Air Quality Action day (AAQD) was declared. These are days when susceptible individuals should take action to limit their exposure to air pollutants by wearing a mask or staying indoors, and avoiding strenuous

activity. We found the days where the instantaneous levels were above the limit in order to isolate the times when the levels were the highest. From there, we examined the meteorological conditions during the formation and breakup of inversions and PM2.5 events. These data were used to inform subsequent analysis, leading to a better understanding of the conditions.

Modeling

We used ArcGIS 10.1 (Esri 2012) for the majority of topographic analysis. The first step was to determine if there was a direct statistical correlation between altitude and PM2.5 concentrations. Using the mobile monitoring data and the associated GPS coordinates, the route and the DEM data were imported into ArcGIS. Then, we used the *Extract Values to Points* tool. Using the mobile monitoring coordinates as the points, we obtained the altitude of each point. The attribute table was then exported into Excel for further analysis.

Previous studies had moderate success modeling wood smoke and air pollutant concentrations using GIS modeling (Larson et al. 2007, Su et al. 2011; Merbitz et al. 2011). These studies used factors such as home heating habits, population density, impermeable surfaces, and urban heat as variables in their prediction of wood smoke concentrations. A main factor in all three studies was overlying topography. They used water catchments and drainage patterns as proxies for describing the airflow over the land. Their studies, unlike the one outlined here, were performed over a very large area. Their study areas ranged from 200 to 1000 km2, whereas the total area of Keene is only
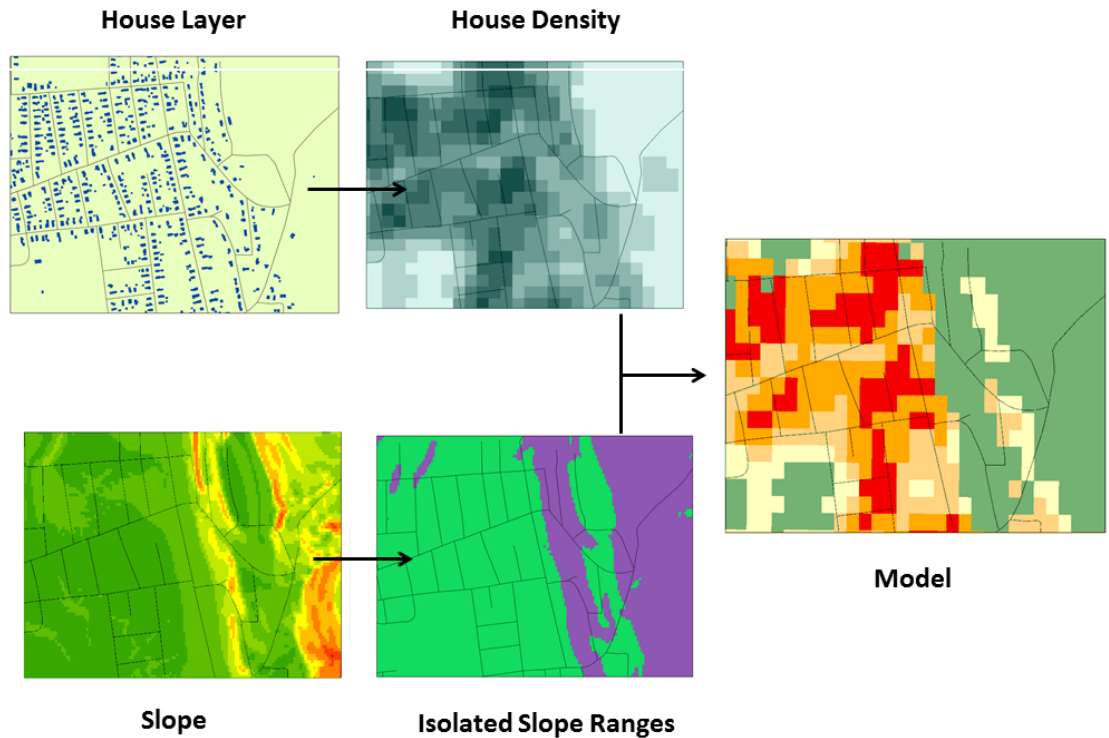
Figure 2. The modeling process

96 km2, of which the urban area is a small fraction. In order to emulate these other studies, we used a DEM to determine if there were multiple catchments in the area. The results showed that there was only one of any significance. If the study area was expanded to cover the entirety of Cheshire County such a factor would be useful, but given the small area of Keene, we did not include drainage basins in the study.

As a proxy for the use of wood as a heating fuel, we used a roughly calculated housing density. A GIS layer containing building footprints contained all buildings, including small sheds and gazebos. We needed to isolate buildings that could be single family homes so we selected those with a footprint greater than 300 ft2 and less than 3,000 ft2. These parameters excluded sheds, as well as large businesses and apartment complexes that would be unlikely to use wood as a fuel source. Given our knowledge about the area, we checked the accuracy of this selection, and deemed it appropriate for inclusion in the study.

Several of the previously mentioned studies state that during an inversion polluted air flows downhill, strengthening the risk of inversions near the base of the incline. Deep valleys in the Rocky Mountains are known to trap pollutants, but the high hills surrounding the valley in which Keene is situated should not contribute to the containment of wood smoke. Considering that the days of concern for the EPA and the study were isolated PM2.5events, the prediction of inversions on those days, and the general attitude that inversions are a primary factor, the downhill airflow of pollutants used in creating the model mirror that of a low altitude winter inversion.
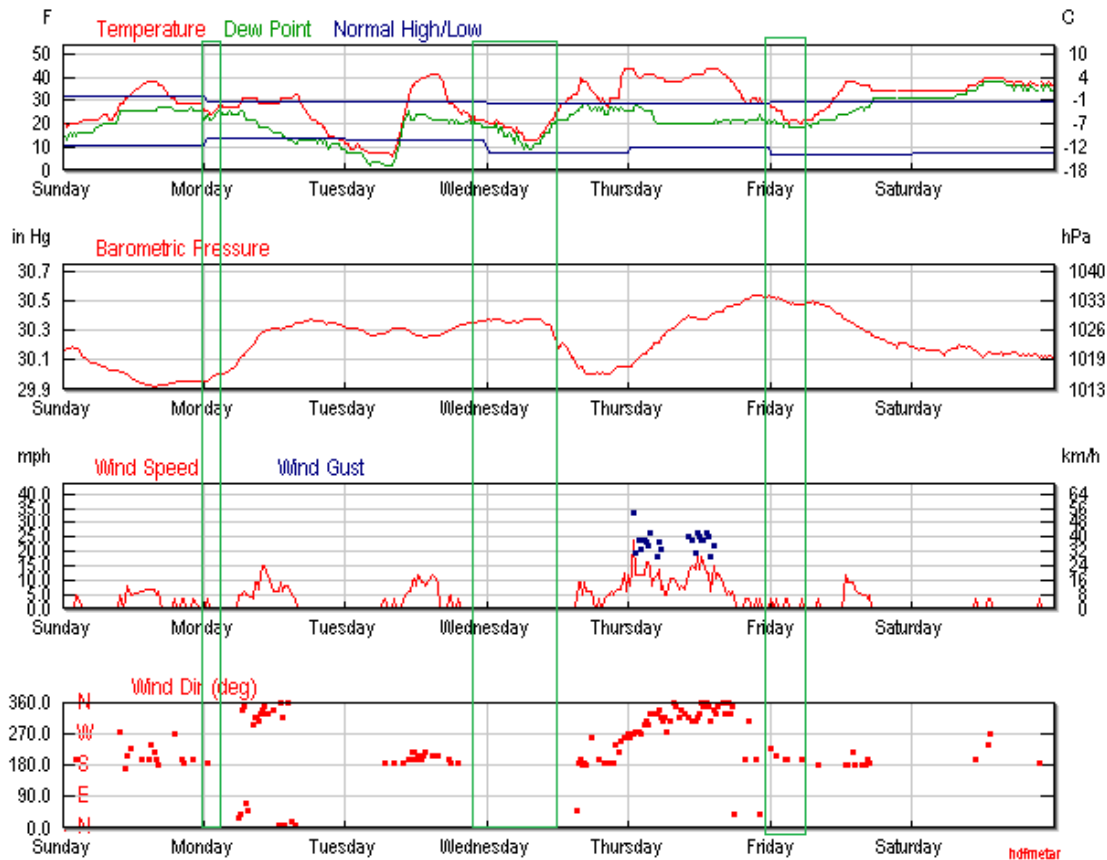
Figure 3. Weather data from the week of January 6th 2013. Keene experienced an acute PM 2.5 events, indicated by the green boxes, the strongest of which was on the night of Tuesday the 8th into Wednesday. Source: NOAA.gov

Given the large, level valley floor in which Keene is situated, it seemed logical that the areas of negligible slope would be a place where pollution would stagnate and collect. DEM's were used to calculate slope in degrees, and then a conditional equation was used to select areas with slope ranging from zero to three degrees. These two factors, housing density and slope, were used to model where pools of PM2.5 may form.

RESULTS

Meteorological Factors

During the winter of 2012-2013, there were several days of relatively extreme PM2.5 events, with seven days exhibiting levels far exceeding the 35µg/m3 EPA limit at the monitoring station. When looking at the meteorological history, several characteristics were apparent.

First was the temperature drop that can lead to an inversion. The temperature change is usually associated with normal diurnal temperature variations, with the coldest temperatures occurring after midnight. The inversions were initiated by a fairly rapid cooling of at least ten degrees. For each event, the average temperature drop from the initial high to the peak of the PM2.5 event was 17 degrees, and ranged from 11 to 33 degrees. This took 11.4 hours, and ranged from 6 to 13 hours. Several days of high PM2.5 data were omitted because they were

a part of long term inversions stemming from the seven mentioned above, or because they represented gaps in the quality assured data.

Dew point is also related to air inversions. As outlined by Whiteman, De Wekker and Haiden (2007), the release of latent heat during the deposition of dew and frost is a notable factor in the creation of ground level temperature inversions. This idea is supported by the meteorological data, as nearly all of the PM2.5 events are accompanied by a dew point very close to the ambient temperature.

It is well known that inversions are prevented and broken up by strong winds, and this is supported by the data. Increases in PM2.5 are greatest when the wind at the monitoring station is less than 1 mph. For the seven exceptional days, the increase in PM2.5 concentration when wind speed was below 1 mph at the monitoring station averages just over 4µg/m3 per hour, with a median value of 4.4µg/m3, and a peak increase of 27µg/m3 . On the seven days with the highest concentrations of pollutants, a rapid rise in PM2.5 levels started at 5:00PM, which could be a result people heating their homes after returning from work. It also coincides with dusk and sunset during the winter months in Keene. There was an average increase of 11.7µg/m3 from 5:00PM to 6:00PM. From 5:00PM to 11:00 PM, which was generally the duration of the rise in concentration for the seven most extreme days, the average increase was a surprising 35.6µg/m3, with the least increase being 30µg/m3. These examples demonstrate that there are specific

meteorological components that precede the onset of air inversions and subsequent increases in PM2.5.

Model

Our model isolates the areas of potentially high PM2.5 concentrations. The model marks the areas with little slope, and clusters of houses that could act as sources for particulates. It logically places a high risk area downtown, where there is a high population density in the middle of the valley. In the map showing areas with a slope of less than one degree, there is very little outside of the valley floor that shows any hazard. However, the results isolated the population clusters in the western and northwestern areas, which are known to have air quality issues.

The model using three degrees of slope or less does a better job showing high risk near the edge of town, and up on the hills to the east of the downtown area. This is important, as there were areas on the hill that had high PM2.5 levels. Overall, it seems that the models predict the PM2.5 readings with moderate success. For the December 3rd data run, both models appear to accurately contain all of the areas that have high PM2.5 concentrations. The run from January 8th, however, is not as accurate. There are a few stretches where there are high levels present, and they sit just outside the boundaries of the areas we created, especially on the valley wall.

Using varying degrees of specificity in terms of the slope seemed to be fairly effective in modifying the model. The map using less than three degrees of slope
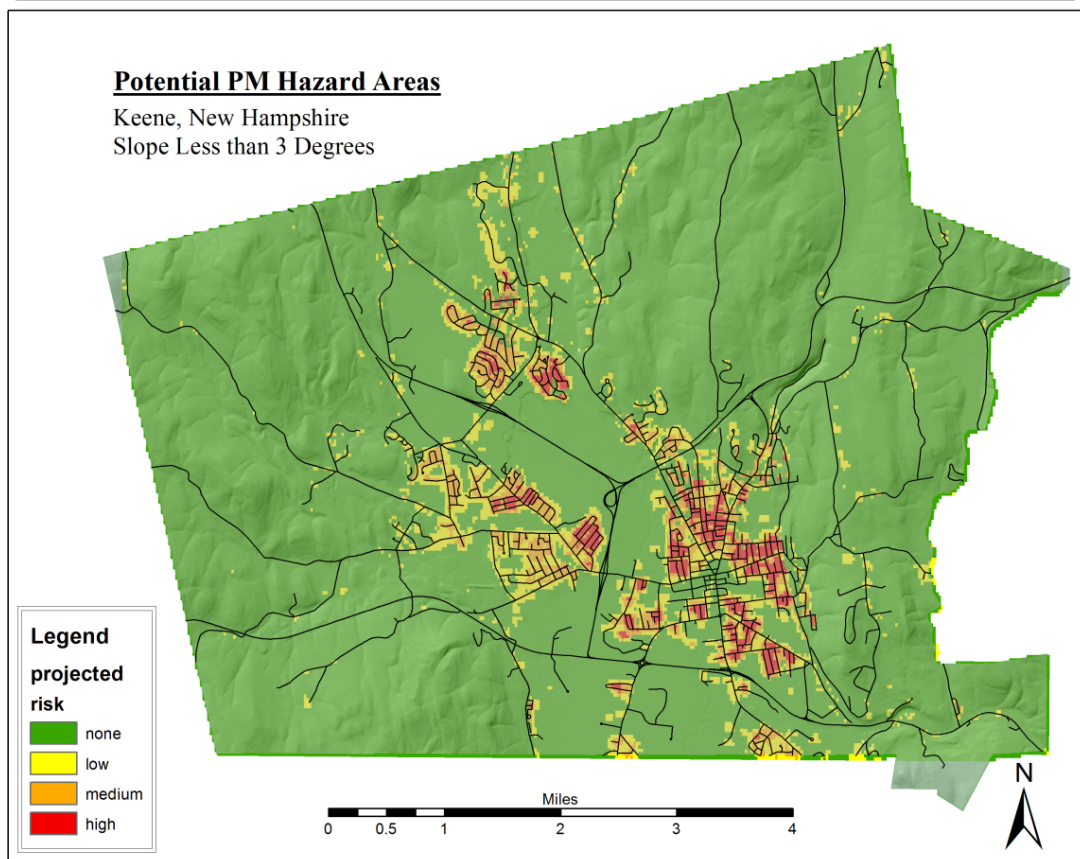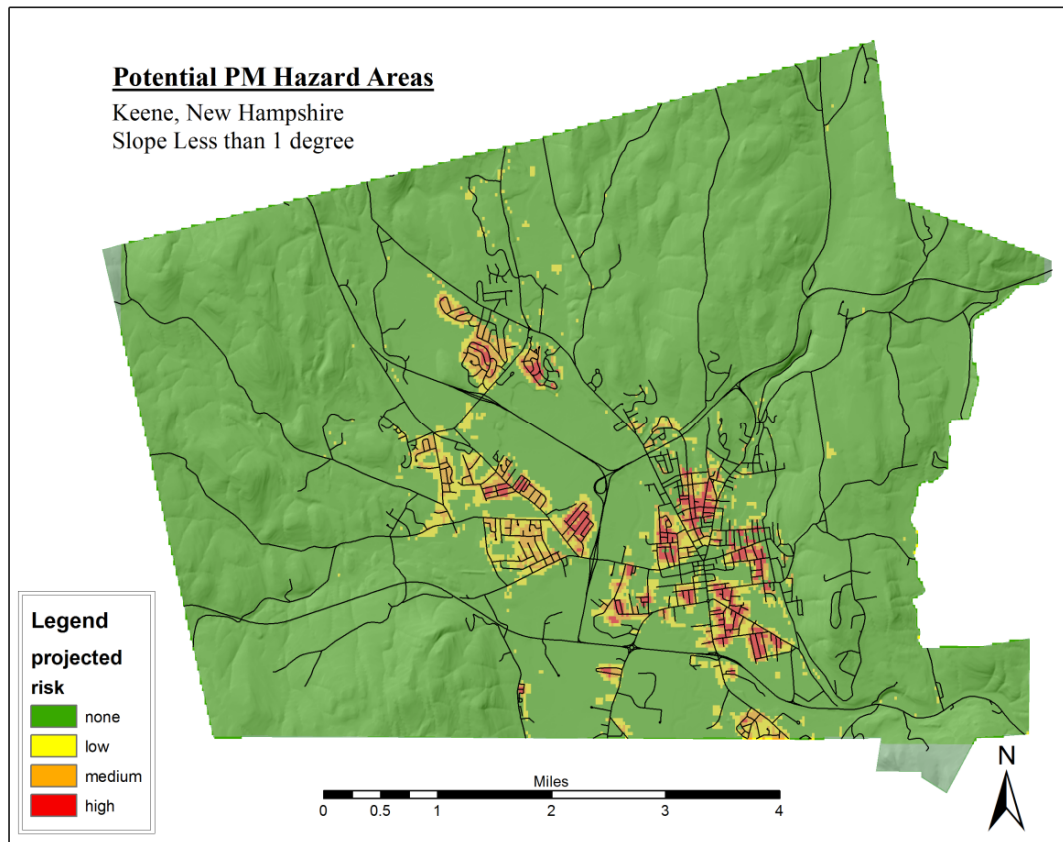
Figure 4. Hazard maps isolating areas of high population density, and slope. They show areas where there would be a risk of inversion lasting more and a few hours.

contained the areas on the January 8th map that were near the center of town, but there was still an anomalous string on the hill. The model with three degrees or less isolates the population cluster on the hill, but does not predict the levels on the road up the hill. However, the map using three degrees of slope accurately depicts the risks for the majority of points for both data runs. Perhaps expanding the tolerance for slope will do a better job of predicting the mobile monitoring levels, but runs the risk of making the model too broad to be accurate. More data is required to develop more accurate models.

CONCLUSIONS

There are specific meteorological conditions that precede the formation of an air inversion, and a subsequent PM2.5 event in Keene. These include a rapid temperature drop of a minimum of 11 degrees Fahrenheit, a dew point close to the ambient temperature, and a relatively windless night. These air inversions trap pollutants within a few meters of ground level, and the concentration will drop significantly after crossing the inversion. There is normally a rapid increase in PM2.5 concentration following 5:00 PM, which continues until after 11:00 PM. Spatially, there are several key features that are important. For levels of PM2.5 to rise, there must be sources present, and they must be arranged in a relatively dense pattern within those parts of the valley that sit below the altitude of air inversions. Otherwise, the particulates will be dispersed or transported elsewhere.

There are several directions for future study. First is a more thorough canvassing pattern for the mobile monitoring data. Given the fairly specific conditions determined by this paper, forecasting air inversions and PM2.5 increases should be relatively easy in conjunction with normal weather forecasting. Armed with this knowledge and a path developed through spatial analytical methods, the distribution of PM2.5 over space could be more thoroughly recorded. This would allow for more advanced geostatistical analysis of the data, using interpolation methods such as Inverse Distance Weighted or Kriging. This would allow for neighborhood-specific forecasting and advisories. Inversion height could also be explored. A tethered weather balloon or pseudo vertical profile from monitoring installations along several axes would be helpful in developing an accurate vertical profile of the stratified air.

A second research avenue would be an exploration of socioeconomic factors. Income dictates many variables in regards to home heating and air quality. Jerett et al. (2001) showed that the location, size, and heat source of homes correlate to the type and amount of pollution that they are exposed to. While Keene may lack the industry that was a point of discussion the report of Jerett et al., the issues concerning clusters of low income households existing in areas topographically inclined to have PM2.5 issues is certainly relevant. The state of the economy might force some to turn cheaper home heating fuels, resulting in increased coal and wood combustion. A simple map overlaying the data used for our
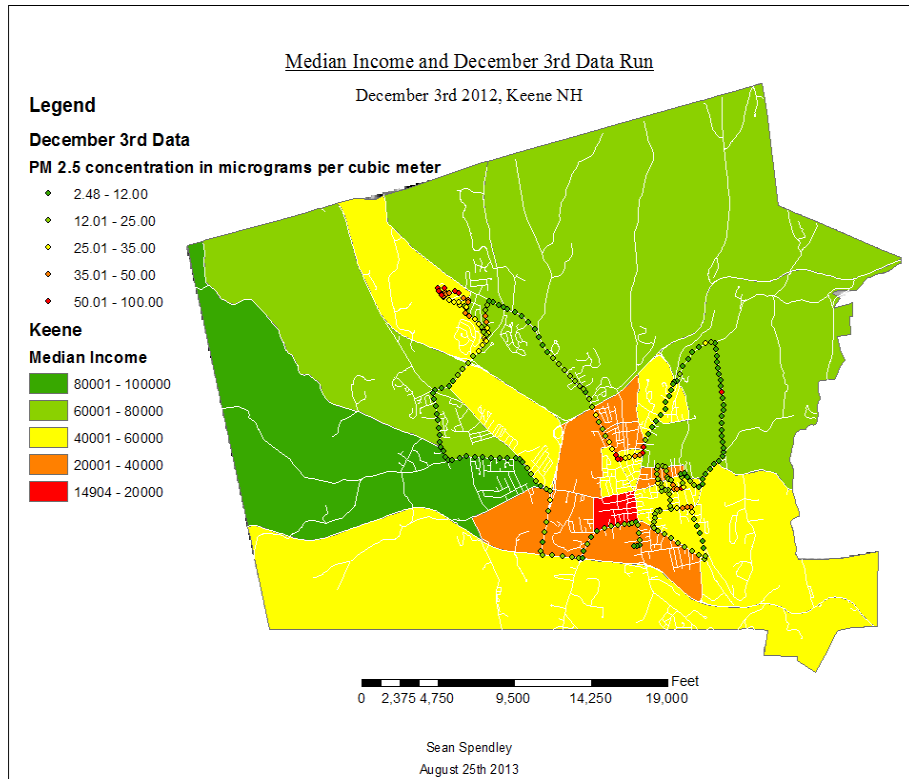
*Figure 5. A simple map showing the December 3rd PM$_{2.5}$ data compared to median income.
Source: 2010 Census 5 Year Projection.*

work and the projected median income shows the potential for a correlation. Considering that Keene is a relatively old city founded in the eighteenth century, the houses may be more likely to have a woodstove or fireplace as a primary heat source. This is not uncommon in the area, and the price of updates may prevent residents from retrofitting their house with gas or electric heaters. A thorough survey of building age and architect may provide additional insights about wood use. Additionally, a thorough survey of home heating fuel and habits would provide more insight into the modeling process. Information regarding type of heating device, and the amount of wood burned would be very useful as they affect the

amount of PM2.5 released into the area. The housing density map could be updated to only those who burn wood, and weighted by said factors. This would undoubtedly give a more accurate depiction of the dispersion of PM2.5 and other pollutants into the Keene area.

References

Baumbach, G. and U. Voght. 2003. Influence of inversion layers on the distribution of air pollutants in urban areas. *Water, Air, and Soil Pollution: Focus*, 3: 65-76

Deng, X., F. Zhang, W. Rui, F. Long, L. Wang, Z. Feng, D. Chen, and W. Ding. 2013. PM2.5-induces oxidative stress triggers autophagy in human lung epithelial A549 cells. *Toxicology in*

Vitro, 27: 1762-1770. DOI: http://dx.doi.org/10.1016/j.tiv.2013.05.004

Gavett, S. H., and H. S. Koren. 2001. The role of particulate matter in exacerbation of atopic asthma. *International Archives of Allergy and Immunology*, 124: 109-112. DOI: http://dx.doi.org/10.1159/000053685

Haley, V. B., T. O. Talbot, and H. D. Felton. 2009. Surveillance of the short-term impact of fine particle air pollution on cardiovascular disease hospitalizations in New York state. *Environmental Health*, 8 (42) DOI: http://dx.doi.org/10.1186/1476-069X-8-42

Janssen, N. A. H., P. Fischer, M. Marra, C. Ameling, and F. R. Cassee. 2013. Short-term effect of PM2.5, PM10 and PM2.5-10 on daily mortality in the Netherlands. *Science of the Total Environment*, 463-464: 20-26. DOI: http://dx.doi.org/10.1016/j.scitotenv.2013.05.062

Jerrett, M., R. T. Burnett, P. Kanaroglou, and J. Eyles. 2001. A GIS – environmental justice analysis of particulate air pollution in Hamilton, Canada. *Environment and Planning* 33: 955-973 DOI: http://dx.doi.org/10.1068/a33137

Larson, T., J. Su, A. Baribeau, M. Buzzelli, E. Setton, and M. Brauer. 2007. A spatial model of urban woodsmoke concentrations. *Environmental Science and Technology*. 41; 2429-2436 DOI: http://dx.doi.org/10.1021/es0614060

Merbitz, H., M. Buttstadt, S. Michael, W. Dott, C. Schneider. 2011. GIS-based identification of spatial variables enhancing heat and poor air quality in urban areas. *Applied Geography*. 33:94-106 DOI: http://dx.doi.org/10.1016/j.apgeog.2011.06.008

Su, S. G., G. Allen, P. J. Miller, and M. Brauer. 2011. Spatial modeling of residential woodsmoke across a non-urban upstate New York region. *Air Quality, Atmosphere and Health* 6:85-94 DOI: http://dx.doi.org/10.1007/s11869-011-0148-1

Vallejo, M., S. Ruiz, A. G. Hermosillo, V. H. Borja-Aburto, M. Cardenas. 2006. Ambient fine particles modify heart rate variability in young adults. *Journal of Exposure Science and Environmental Epidemiology*, 16 (2): 125-130. DOI: http://dx.doi.org/10.1038/sj.jea.7500447

Wallace, J., D. Corr, and P. Kanaroglou. 2010. Topographic and spatial impacts of temperature inversions on air quality using mobile air pollution surveys. *Science of the Total Environment*, 408: 5086-5096 DOI: http://dx.doi.org/10.1016/j.scitotenv.2010.06.020

Whiteman, C.D., S. F. J. De Wekker, and T. Haiden. 2007. Effect of dewfall and frostfall on nighttime cooling in a small, closed basin. *Journal of Applied Meteorology and Climatology*, 46: 3-13 DOI: http://dx.doi.org/10.1175/JAM2453.1