Predicting Areas of High Diesel Particulate Matter Emissions in Phoenix, Arizona, Using Spatial Analysis Techniques

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ABSTRACT

Growing evidence suggests that inhalation exposure to diesel exhaust, including diesel particulate matter (DPM), causes acute and chronic health effects. As a result, interest in monitoring diesel exhaust has increased. Maps of emissions sources, emissions activity data, and meteorology were combined within a geographic information systems (GIS) suitability model to produce a composite map identifying regions where DPM emissions are likely to be high. The results of the GIS model were compared to (a) locations of existing monitoring sites in Phoenix and (b) spatial distribution of population. Results indicate that two existing sites are located in areas where DPM emissions are predicted to be high; however, incorporating meteorology as a factor showed that one site is located upwind of a predicted high DPM area. Consideration of population density showed high density in two areas that appear to be moderately influenced by DPM.

INTRODUCTION

This work was funded by the Arizona Department of Environmental Quality (ADEQ) to support the ADEQ toxics monitoring program. The objective of this work was to use geographic information system (GIS) technology to identify areas within the Phoenix region where diesel particulate matter (DPM) emissions are likely to be high and to identify locations potentially suitable for placing toxics monitors to better measure DPM. Figure 1 illustrates the study domain and locations of existing long-term toxics monitoring sites in Phoenix.

Figure1. Map of the Phoenix area depicting long-term air toxics monitoring sites (blue triangles), topography, urban features, and tribal lands (red polygons).

Diesel Particulate Matter

DPM is part of a complex mixture that makes up diesel exhaust. Diesel exhaust is commonly found throughout the environment and is estimated by the U.S. Environmental Protection Agency's (EPA's) National Scale Assessment (NSA) to contribute to human health risk[1] and can cause acute and chronic health effects.[2-4] It is also a significant contributor to $PM_{2.5}$ (particulate matter that is 2.5 micrometers or smaller in size) concentrations and regional haze.[5-8] As such, DPM has been the focus of ambient monitoring and long-term epidemiological studies.

Diesel exhaust is emitted by a broad range of diesel engines including on-road diesel trucks, locomotives, marine vessels, and heavy duty equipment. These sources emit different amounts of DPM and are often spatially dispersed within an urban area. DPM concentrations are highest and have the best correlation with respiratory distress near the areas of highest diesel usage.[9-11] DPM cannot be directly measured; elemental carbon (EC) or black carbon (BC) measurements are often used as a surrogate, although measurements of EC or BC alone are insufficient to quantify diesel contributions. Different sources of DPM emit different amounts of EC or BC relative to organic carbon, and analytical methods for EC and BC differ,[12,13] making integrated spatial monitoring of DPM difficult. Therefore, novel approaches must be developed to determine areas of DPM influence, to assist in identifying suitable monitoring locations to target DPM, and to provide data which may be useful to assess whether sensitive populations may be adversely impacted by DPM.

Suitability Modeling

Suitability modeling is a method for identifying suitable monitoring locations based on specific criteria. For example, suitability modeling can be used to determine possible locations for new air quality monitoring sites based on criteria such as emissions source influence, proximity to populated places, urban or rural land use, site accessibility, etc. The idea is that map layers representing these important criteria can be compiled and merged to develop a composite map representing the combination of important criteria for a defined area. Furthermore, each map layer input can be assigned a weighting factor based on the relative importance of each layer in the overall suitability model. For example, when determining suitable locations for placing a new air quality monitor, each of the important criteria can be prioritized in terms of its relative importance. If the monitoring objective is to measure air quality in densely populated places, then a map layer representing population density would be given priority, and a corresponding high weighting factor, in the overall model, and the resulting suitability map output would favor areas of high population density.

The Environmental Systems Research Institute (ESRI) ArcGIS® software, Spatial Analyst, was used for this analysis. Spatial Analyst is a raster- or grid-based software that provides a platform for developing and manipulating gridded data. Spatial Analyst can be used to develop suitability models that produce maps highlighting “suitable” geographic regions based on defined model criteria and weighting schemes. Figure 2 illustrates the general steps used to develop a suitability model.

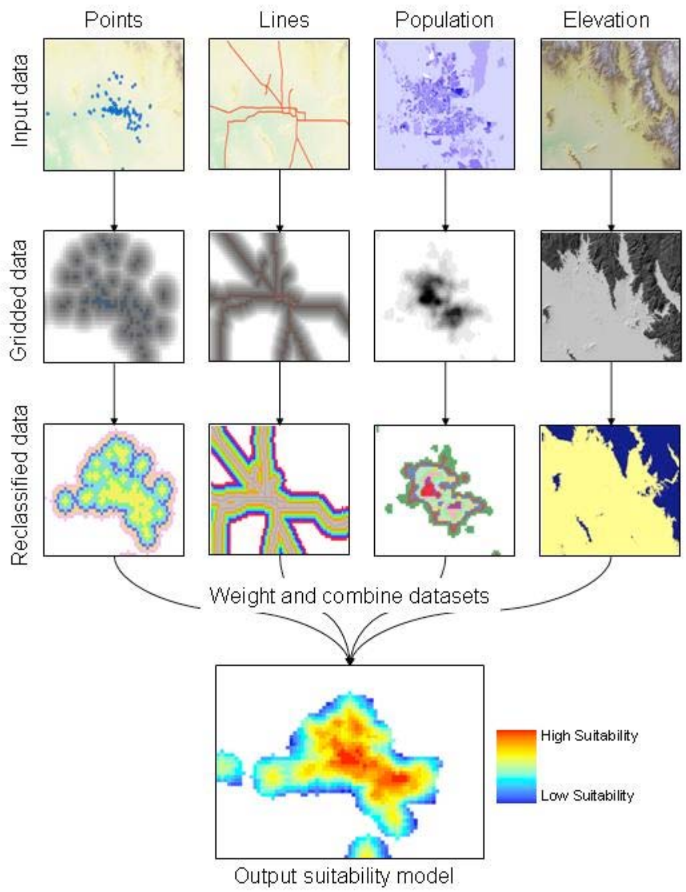

Figure 2. Conceptual approach for building a suitability model.

METHODS

The following three general steps were performed to identify areas in the Phoenix region likely to be influenced by DPM:

1. Assess the emission inventory to determine the predominate sources of DPM in the region and the best available data to represent the spatial pattern of the identified emissions sources in the Phoenix region.
2. Acquire and process the spatial data (map layers) required for the analysis.

3. Develop the suitability model to predict areas likely to have high DPM emissions.

The first step of the analysis involved summarizing the emission inventory for the Phoenix region to identify the predominant sources of DPM. Next, the best available corresponding spatial data, or map layers, were identified to represent the spatial pattern of emissions for the predominant DPM source categories. The second step of the analysis involved acquiring and processing the spatial data for the suitability model. The third and last step involved developing and running the suitability model for different model scenarios. The remainder of this section discusses each of the three general steps listed above.

Step 1: Emission Inventory Assessment

The first step in this analysis was to assess the emission inventory for the Phoenix area and to identify the important sources of DPM in the region. The 1999 U.S. EPA National Emission Inventory (NEI) was acquired and processed for Maricopa and Pinal counties. Diesel sources tend to emit substantial levels of $PM_{2.5}$; therefore, the NEI for Maricopa and Pinal Counties was assessed to determine the predominant sources of $PM_{2.5}$. Table 1 lists the major sources, emissions, and percent contribution to total $PM_{2.5}$ emissions for Maricopa and Pinal Counties.

Table 1. Major source categories, emissions, and percent contribution of total $PM_{2.5}$ for Maricopa and Pinal counties as reported in the 1999 NEI. Note these sources combined account for 90% of total $PM_{2.5}$ emissions.

Source Type	$PM_{2.5}$ (tons/yr)	Percentage of Total $PM_{2.5}$ Inventory
Road construction (dust and exhaust)	7,036	18.6%
Open burning	6,959	18.4%
Heavy construction (dust and exhaust)	3,575	9.4%
All paved roads fugitives (dust)	3,389	8.9%
All unpaved roads fugitives (dust)	2,559	6.7%
Agriculture – crops tilling (dust)	2,514	6.6%
Forest wildfires	1,970	5.2%
Managed burning, prescribed	1,499	4.0%
Heavy-heavy duty diesel vehicles	1,083	2.9%
General building construction (dust and exhaust)	1,036	2.7%
Diesel construction and mining equipment	1,012	2.7%
Residential wood	694	1.8%
Gasoline lawn and garden equipment	416	1.1%

Figure 3 details the source breakdown for $PM_{2.5}$ emissions in Maricopa and Pinal Counties. Approximately 12% (4,372 tons/year) of total $PM_{2.5}$ emissions in these counties emanates from on- and non-road mobile sources. Area and point sources are responsible for about 86% (32,851 tons/year) and 2% (694 tons/year) of total $PM_{2.5}$ emissions, respectively. As indicated in Table 1 and Figure 3, the top two sources of $PM_{2.5}$ are road construction activities and open burning. Road construction activities include both exhaust and dust emissions. Open burning and wildfire emissions were not considered important for this analysis because they are not a significant source of DPM. Moreover, open burning and wildfires tend to occur in the rural areas outside of Phoenix, and the focus of this work is on more densely populated urban areas. Because diesel emissions are the primary focus of this analysis, sources of dust, such as road construction and fugitive road dust, were also excluded when possible. In some cases, sources of dust and exhaust were combined into one source category; emissions for these combined categories were included in the analysis.

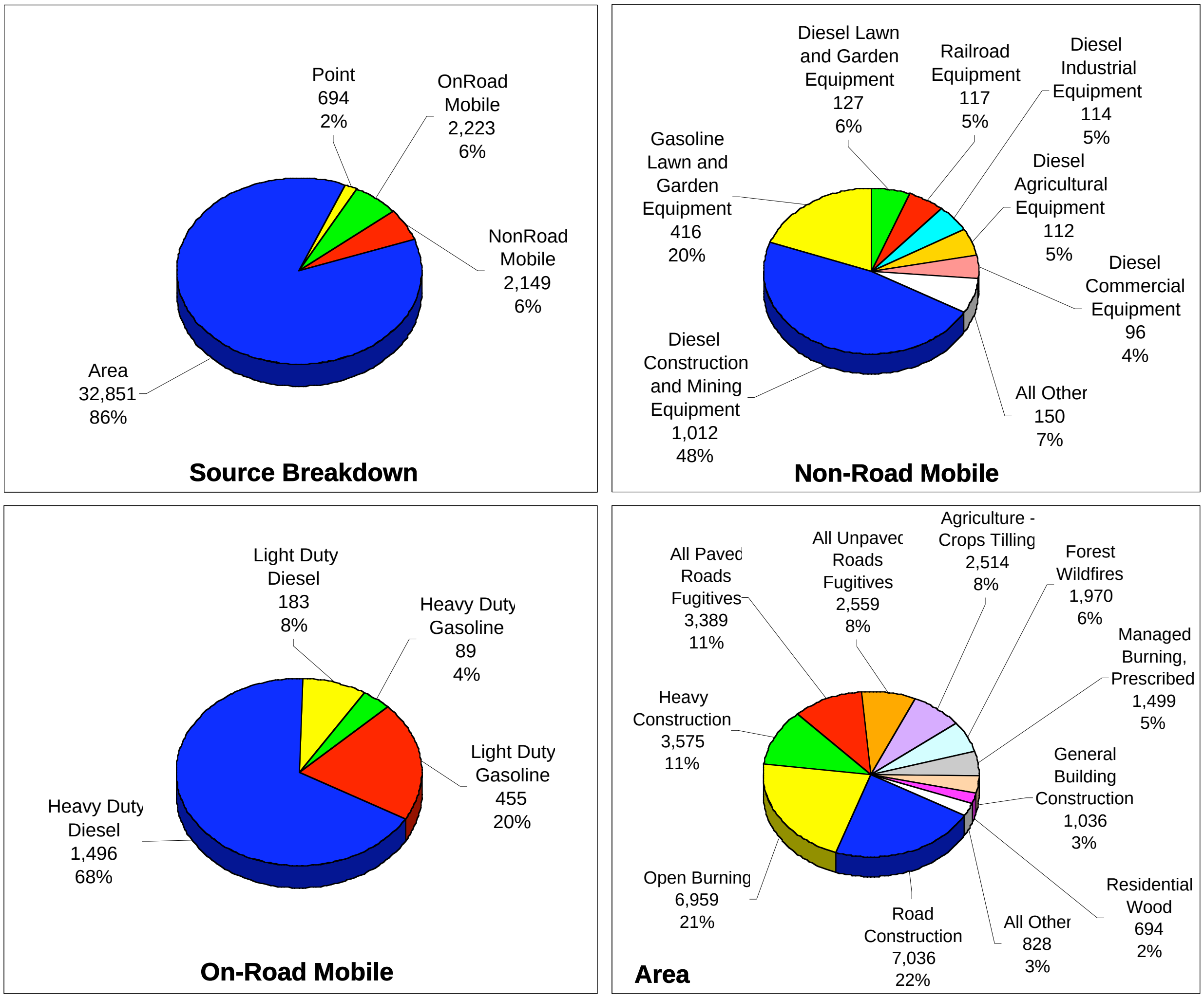

Figure 3. Emissions source contributions to total $PM_{2.5}$ for Maricopa and Pinal counties as reported in the 1999 NEI.

To help quantify the sources of $PM_{2.5}$ listed in Table 1 in terms of their potential contribution to DPM, PM speciation profiles were acquired from the California Air Resources Board (CARB) and EPA's SPECIATE Database[19,20] to determine the relative mass fractions of EC from each of the major sources as a surrogate for diesel emissions.[6,21,22] The speciation profiles were multiplied by the mass of emissions for select sources to arrive at an approximate mass for EC by source type. Table 2 lists the EC contributions for a subset of sources from Table 1. As shown in Table 2, on-road heavy-duty diesel vehicles have the highest relative levels of EC, followed by diesel construction, and on-road gasoline vehicles.

Table 2. Elemental carbon contributions for emissions sources in the $PM_{2.5}$ emission inventory for Maricopa and Pinal counties. The EC weight percent data are from ARB's Speciation Profile Library.

Emissions Source	$PM_{2.5}$ (tons/year)	EC weight percent[a]	EC (tons/year)
All heavy duty diesel vehicles	1,496	0.264	395
Diesel construction and mining equipment	1,012	0.150	152
All highway vehicles – gasoline	544	0.200	109
Gasoline lawn and garden equipment	416	0.200	83
$PM_{2.5}$ point sources	694	Differs by source type	54
Diesel lawn and garden equipment	127	0.150	19
Diesel commercial equipment	96	0.150	14
Railroad equipment	117	0.100	12
Gasoline construction and mining equipment	28	0.200	6
Aircraft	25	0.150	4
Gasoline commercial equipment	21	0.200	4

[a] California Air Resources Board - Speciation Profiles and Size Fractions (http://www.arb.ca.gov/ei/speciate/speciate.htm)

Step 2: Data Acquisition and Processing

Because we are interested in identifying locations where DPM emissions are likely to be high, we must be able to spatially characterize the distribution of emissions for each major DPM source category. For example, a map of roadways and associated traffic volumes for heavy- and light-duty vehicles could be used to characterize the spatial distribution of emissions from on-road mobile sources. A less straightforward example is construction equipment. Because construction equipment is a mobile source and the exact locations of emissions releases are less known, surrogate map layers can be used to represent emissions from these source types. For example, maps indicating areas of new development and construction could be used as a surrogate for diesel construction equipment emissions.

An important aspect of this analysis is assessing the proximity of identified areas where DPM is likely high in relation to population density. It is of particular interest to know where the regions of likely high DPM are in relation to sensitive population groups (i.e., elderly people and children). Geophysical land features and meteorology are also important to include in the model because they influence the dispersion of emissions.

Several sources of spatial data were identified and assessed for use in this analysis. Table 3 lists each of the major emissions sources and the corresponding map layer assigned to represent the spatial distribution of emissions in the suitability model. Population data by Census block for 2000 were acquired from the U.S. Census Bureau. Digital elevation model (DEM) topography data were acquired from the United States Geological Survey (USGS).

Table 3. Spatial data assigned to each emissions source.

Emissions Source	Map Layer Assigned to Represent Spatial Distribution of Emissions
Highway vehicles – diesel	Locations of roadways and corresponding heavy duty vehicle AADT[a], locations of major transportation hubs[b]
Diesel construction and mining equipment	Maps of residential and commercial development areas[c]
Highway vehicles – gasoline	Locations of roadways and corresponding light duty vehicle AADT[a]
Gasoline lawn and garden equipment	Land use[d]
Diesel lawn and garden equipment	Land use[d]
Railroad equipment	Locations of transportation hubs, locations of railroad links[e]
Diesel commercial equipment	Maps of development areas[d]
Gasoline construction and mining equipment	Maps of development areas[d]
Aircraft	Airport locations[e]
Gasoline commercial equipment	Maps of development areas[d]
$PM_{2.5}$ point sources	Locations of point sources[f]

[a] Arizona Department of Transportation, 2000
[b] National Transportation Atlas Data, Bureau of Transportation Statistics, 2002
[c] Maricopa Association of Governments (MAG), Residential/Commercial Completions, 2000-2003
[d] Maricopa Association of Governments, Existing Land use, 2000
[e] National Transportation Atlas Data, Bureau of Transportation Statistics, 2002
[f] EPA's Aerometric Information Retrieval System (AIRS), now Air Quality System (AQS), 1999

Spatial data representing on- and non-road mobile sources were acquired from a variety of sources. Road network maps containing annual average daily traffic (AADT) data for heavy- and light-duty vehicles in the Phoenix area were obtained from the Arizona Department of Transportation (ADOT). AADT indicates of the relative on-road mobile source activity, and corresponding emissions levels, in the Phoenix area. Figure 4 shows the AADT road network map. The locations of airport, rail lines, and transportation distribution facilities, also sources of DPM, were obtained from the U.S. Bureau of Transportation Statistics (BTS).

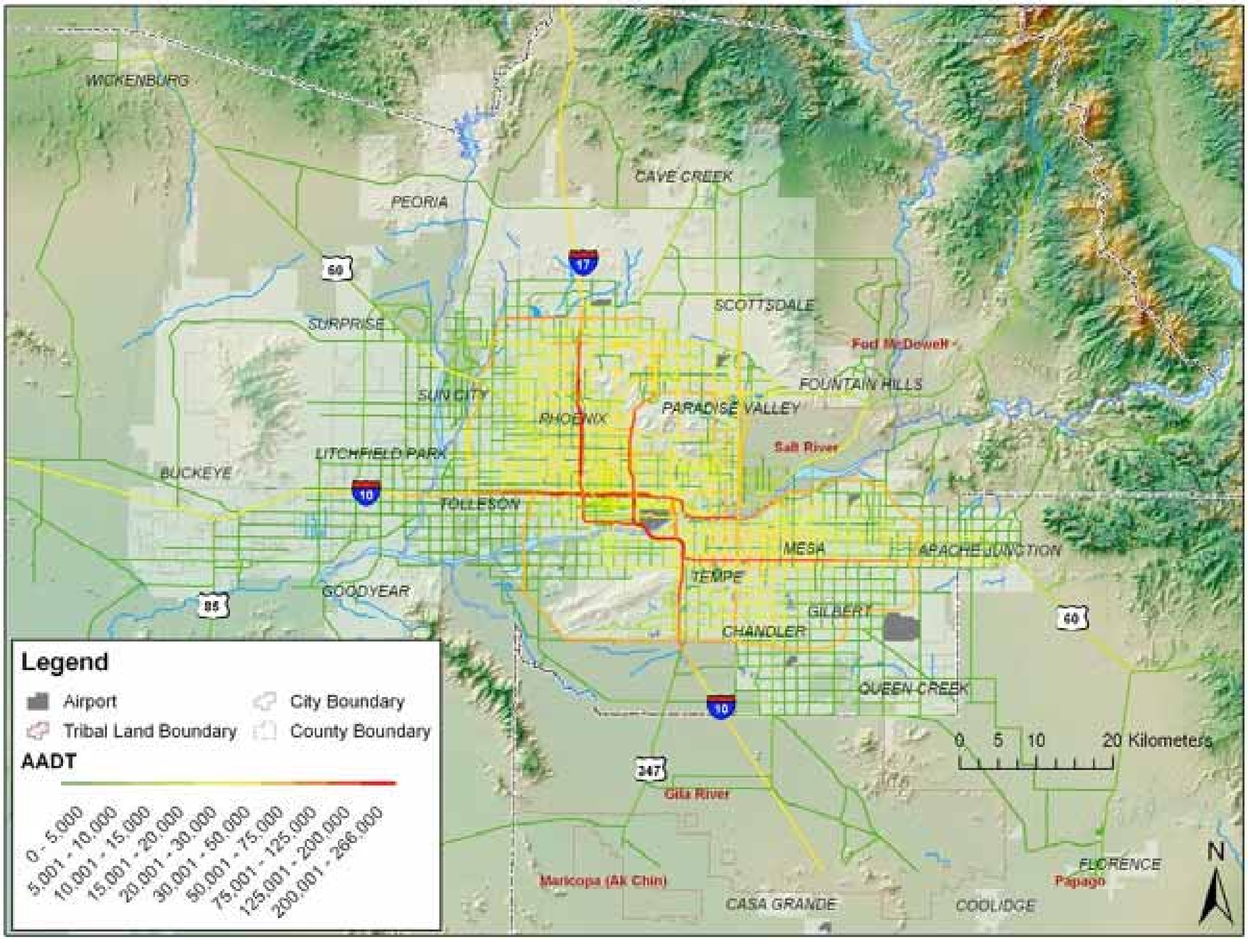

Figure 4. Annual average daily traffic volume (AADT) for the Phoenix area.

Spatial surrogate data were acquired to represent the spatial pattern of DPM emissions from non-road mobile source equipment including construction equipment and lawn and garden equipment. Because the majority of construction equipment usage occurs during the development and construction of residential and commercial buildings, maps of residential and commercial development completions from 2000-2003 were obtained from the Maricopa Association of Governments (MAG). The square footage of residential development and the acreage of commercial development were used as indicators of the relative emissions activity for construction equipment. To spatially represent the distribution of emissions from lawn and garden equipment, land use data identifying large irrigated grass areas (i.e., golf courses and cemeteries) were obtained from MAG. Figure 5 identifies the locations of golf courses, cemeteries, and large development areas in the Phoenix area.

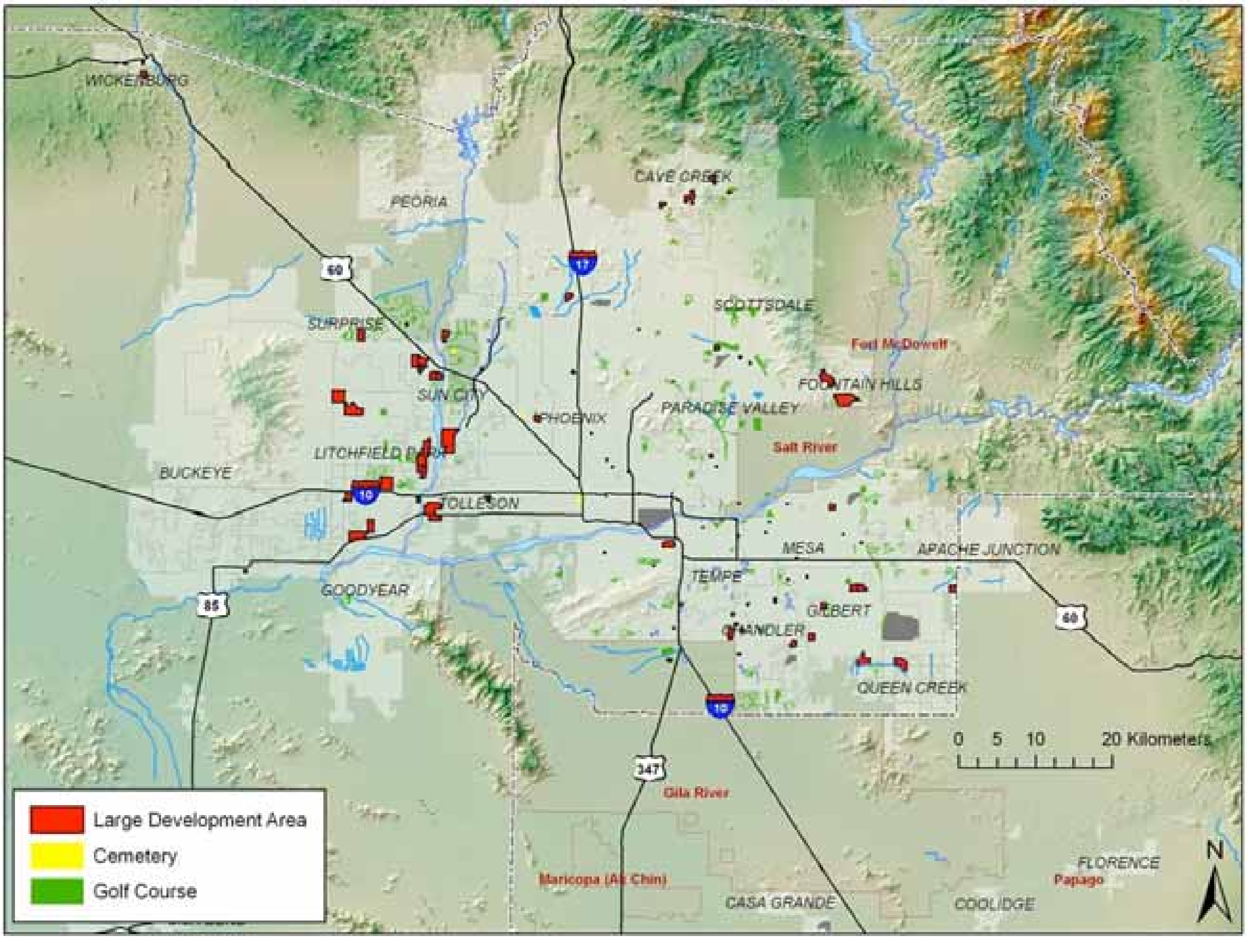

Figure 5. Large development areas, golf courses, and cemeteries in the Phoenix area.

Emissions data for large point sources were obtained from the EPA's Air Quality System (AQS) and were used to map the magnitude of $PM_{2.5}$ emissions in the Phoenix area. Figure 6 identifies the location and emissions contributions of large industrial facilities emitting $PM_{2.5}$ in the Phoenix area. Point source locations were used to investigate the impact other $PM_{2.5}$ sources would have on effectively assessing areas of potentially high DPM concentrations. DEM data were acquired to produce a three-dimensional visualization of the regional topography. DEM data were also used to characterize the potential topographical influence on meteorology and the distribution and transport of emissions.

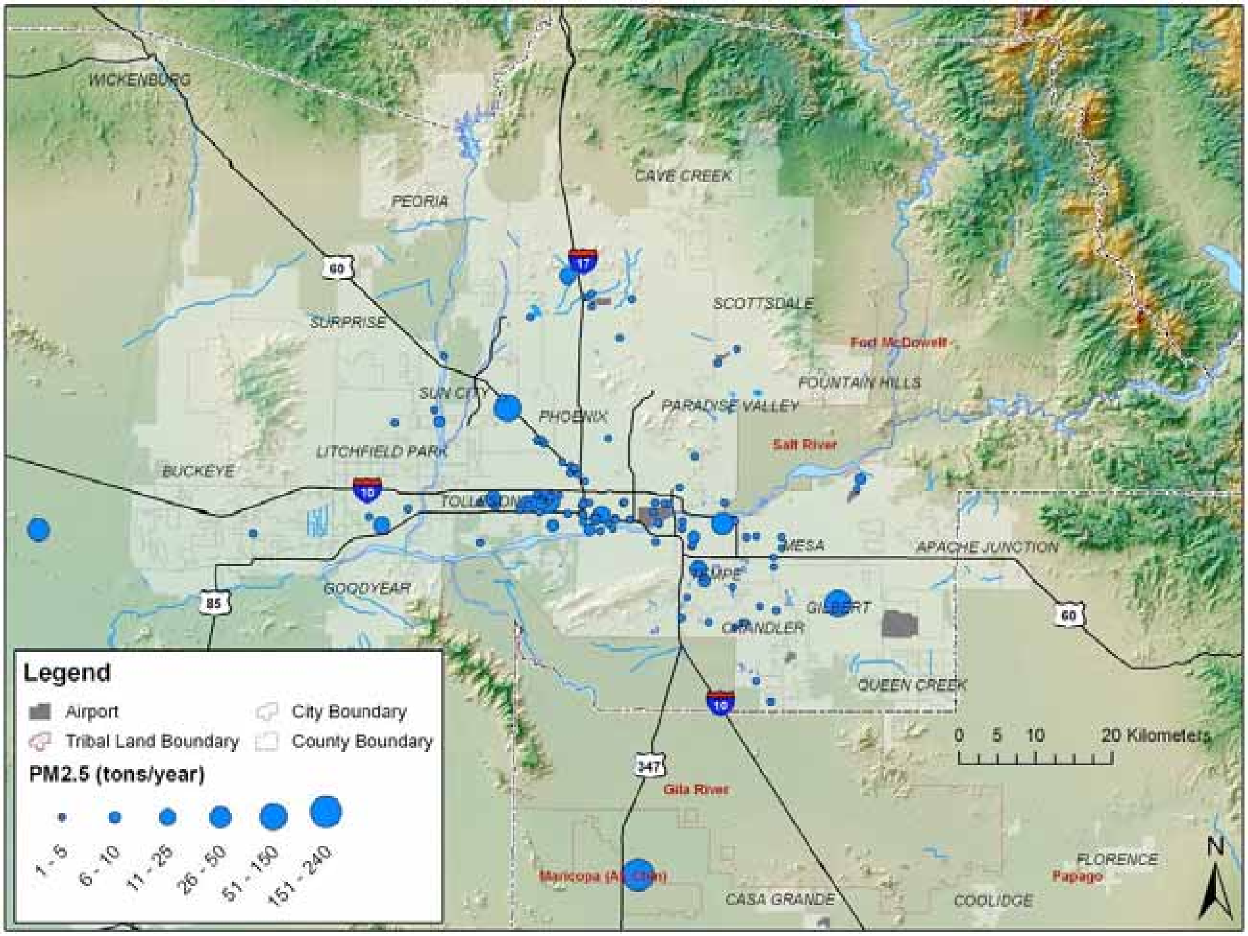

Figure 6. Location and magnitude of emissions for $PM_{2.5}$ point sources in Phoenix.

A unique feature of this analysis was the attempt to account for meteorological influences in the suitability analysis. For example, not only do we expect DPM concentrations to be higher closer to an emission source, but we also expect concentrations to be higher in areas downwind of the source. Wind speed and direction data were acquired for 12 monitoring sites within the Phoenix area from the Central California Air Quality Studies (CCAQS) database. Annual average gridded wind fields were developed using CCAQS data from meteorological stations to represent the predominant wind direction throughout the region. Figure 7 is a wind rose plot of the annual average wind speed and direction for Phoenix based on data from 2001-2003. As shown in Figure 7, the colored coded bars represent the percent and speed of wind from directions ranging 1 to 360 degrees.

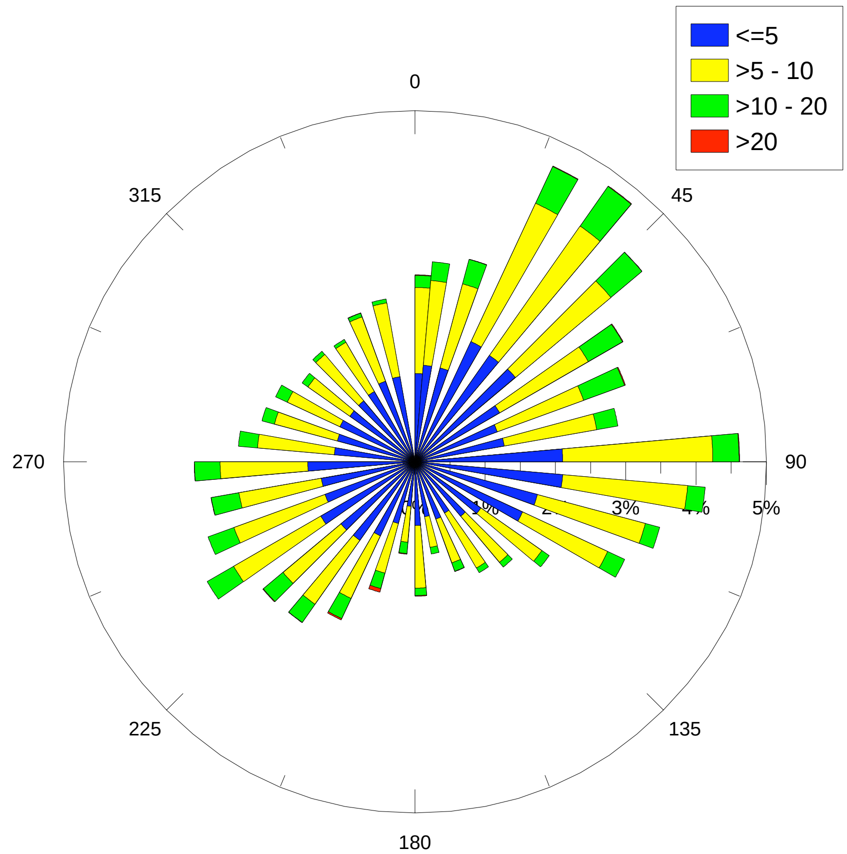

Figure 7. Predominant annual (2001-2003) wind rose for the Phoenix area. Wind speed measured in meters per second.

Population data were acquired from the 2000 U.S. Census and were used to create maps of the regional population distribution. The population data were used to investigate the placement of existing monitors relative to total population and sensitive population groups. Sensitive population groups were defined as children (5 and under) and the elderly (65 and older). Figure 8 shows the (a) total and (b) sensitive population density distribution for Phoenix. As shown in Figure 8, central Phoenix has the highest total population density in the region, whereas Sun City and Mesa have the highest density of sensitive population groups.

(a)

(b)

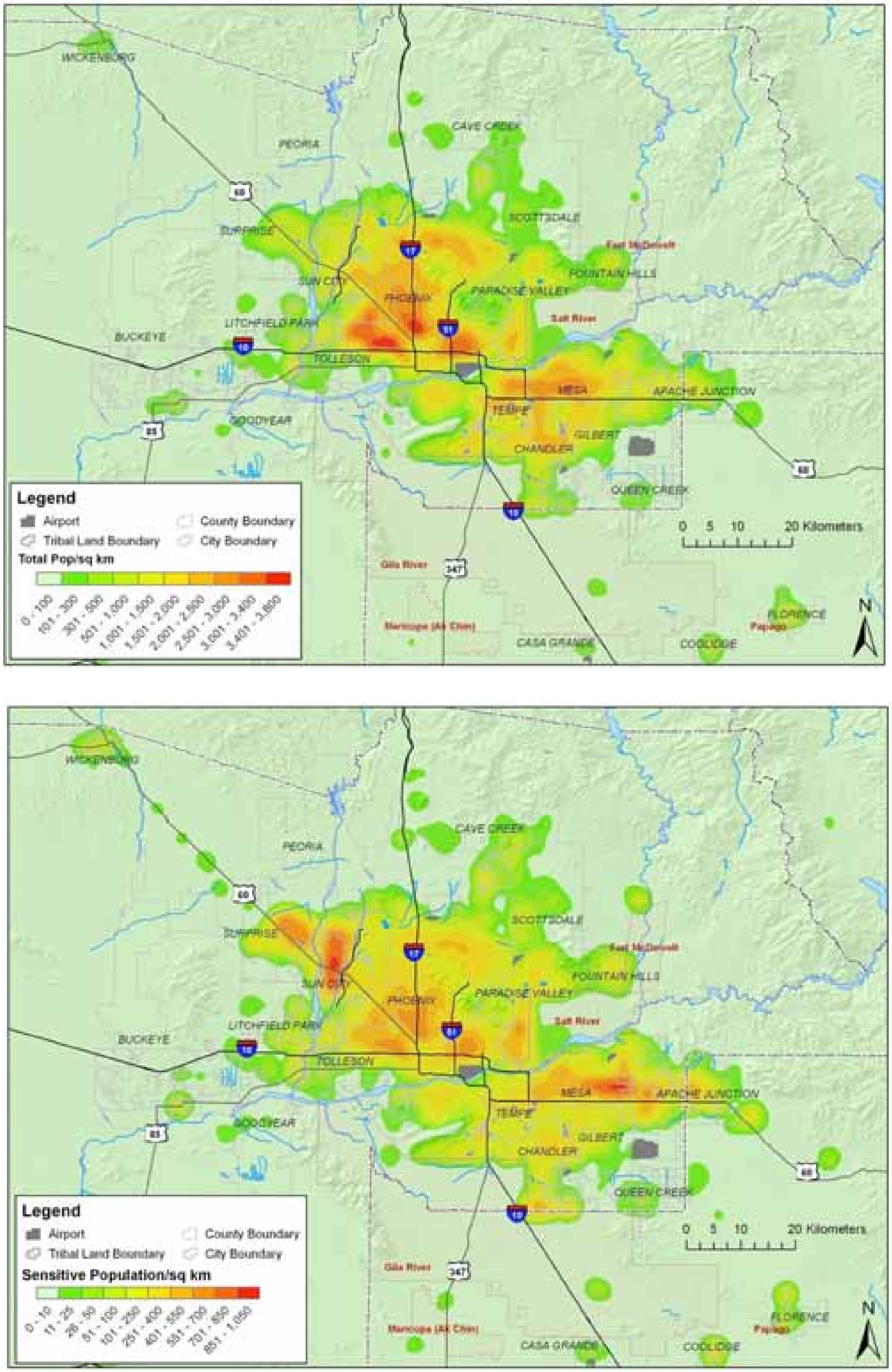

Figure 8. Phoenix area (a) total population density and (b) sensitive population (age 65 years and over and 5 years and under) density.

Step 3: Suitability Model Development

Three model scenarios were defined to examine the spatial distribution of DPM emissions: (1) development of a composite map to represent the spatial distribution and density of DPM emissions based on the locations of DPM sources (hot spots), (2) proximity of total population to DPM sources, and (3) proximity of sensitive population groups to DPM sources. Each of the three model scenarios were developed both including and excluding meteorological effects (wind speed and direction). The model scenarios were developed by assessing each emissions source and its relative contribution of EC emissions (used in this analysis as a surrogate for DPM emissions). Each map layer representing the spatial pattern of emissions was assigned a weighting factor to determine its contribution to the outcome of the overall suitability model depending on the objective of each model scenario.

The first step in developing the modeling scenarios was to determine which source types contribute significantly to EC emissions. As shown in Figure 3, area sources (including non-road construction equipment) are the largest contributor to total $PM_{2.5}$ emissions. On-road mobile sources are the next largest contributor and point sources contribute only 2% to total $PM_{2.5}$ emissions. As noted in Table 2, the highest EC contribution comes from heavy-duty highway diesel vehicles, followed by diesel construction, and gasoline vehicles.

The second step in developing the modeling scenarios was to develop a weighting factor for each map layer based on the EC contributions corresponding to the emissions source represented by the map layer. Table 4 summarizes the relative EC contributions corresponding to each map layer and the assigned weighting factor. For example, EC contributions from diesel construction and mining equipment, diesel commercial equipment, gasoline construction and mining equipment, and gasoline commercial equipment were combined to produce the weighting factor for the commercial/residential development map layer. As shown in Table 4, heavy duty vehicle activity was assigned the highest weighting factor in model scenario 1 because of its high EC contribution, followed by commercial/residential development areas representing heavy-duty construction emissions. Total population density and sensitive population density map layers were assigned the highest weighting factor in model scenarios 2 and 3, respectively, to identify areas where DPM emissions are likely to impact highly populated areas.

Table 4. Weighting scheme for suitability analysis for monitoring diesel emissions and population exposure to diesel emissions.

Layer	Weighting Scheme			Weighting Criteria
	(1) Hot Spot	(2) Total Population	(3) Sensitive Population	
Density of total population	-	40%	-	High population density = more suitable
Density of sensitive population	-	-	40%	High population density = more suitable
Heavy duty vehicle activity	20%	12%	12%	High traffic density = more suitable
Light duty vehicle activity	15%	9%	9%	High traffic density = more suitable
Transportation distribution facility	20%	12%	12%	Close to facility = more suitable
Lawn/garden activity areas	12%	7.2%	7.2%	High activity density = more suitable
Commercial/residential construction activity areas	20%	12%	12%	High activity density = more suitable
Distance to airports	2%	1.2%	1.2%	Close to airport = more suitable
Distance to railroads	2%	1.2%	1.2%	Close to railroad = more suitable
$PM_{2.5}$ point source activity	9%	5.4%	5.4%	High $PM_{2.5}$ emissions density = less suitable

The map calculator within the ESRI Spatial Analyst extension was used to weight and combine the map layers and produce a suitability model. Equation 1 is an example of a map calculator expression:

([Layer_1]*.20 + [Layer_2]*.30 + [Layer_3]*.50) **(1)**

In this example calculation, Layer_1, Layer_2, and Layer_3 represent individual map layers, and decimal values are the weighting factors applied to each layer. Layer 3 is weighted most heavily because it should have the most influence in the model.

RESULTS AND DISCUSSION

The results of this analysis are presented as suitability maps indicating areas of high (red) to low (light green) suitability. Low suitability includes areas exhibiting unfavorable characteristics for placing monitors to measure DPM. For example, we are interested in placing monitors in locations with high population density; therefore, areas of low population density would be classified as low suitability, while areas of high population density would be classified as high suitability. Medium suitability is defined as areas with some suitable features that heighten the importance of an area for emissions activity, population density, or meteorology. High suitability indicates areas where significant and favorable features (i.e., DPM emissions sources, population density, and wind direction) converge.

Figure 9 shows the results of the hot spot (model scenario 1) suitability analysis without considering meteorological influence. Areas of potentially high DPM emissions are in red; these are areas in which a monitor would be well-placed to measure a mix of sources that emit DPM. Areas near the intersection of Interstate Highways 10 and 17, and the downtown section of Interstate Highway 10, are identified as suitable areas for monitoring DPM. Figure 10 shows the model scenario 1 incorporating the influence of meteorology. The existing Bethune School monitoring site is identified in Figure 10 as suitable for monitoring DPM. The area identified as highly suitable surrounding downtown Phoenix shifts to the southwest when meteorology is used in the model.

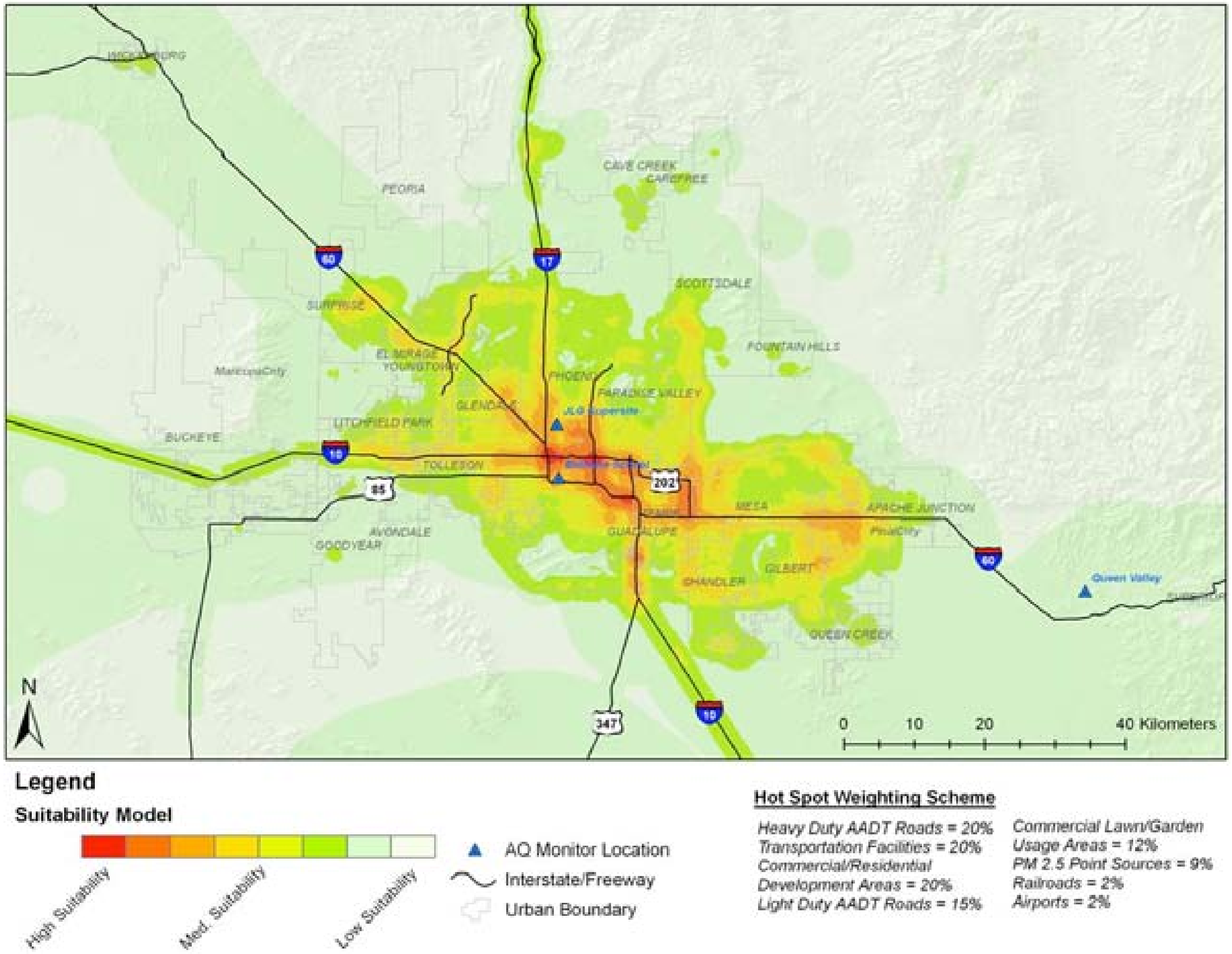

Figure 9. Hot spot suitability analysis without meteorological influence

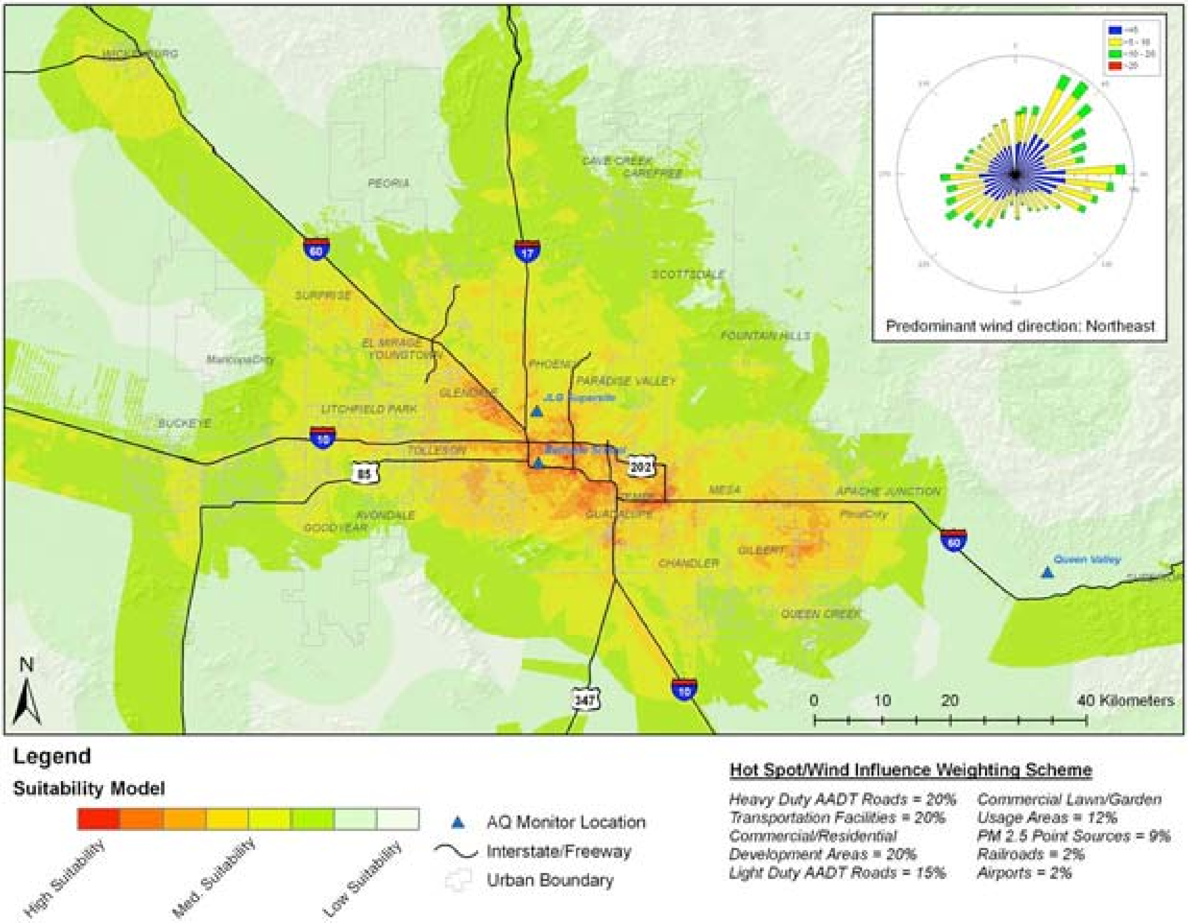

Figure 10. Hot spot suitability analysis with meteorological influence

Figure 11 shows the results from the model scenario 2 analysis for total population accounting for meteorology. When population and meteorology are considered in the suitability model, the suitable areas are located just southwest of high population density regions. For example, the JLG Supersite is located near an area of high population. When the predominantly southwesterly wind influence is added to the model, the resulting map indicates that regions southwest of the Supersite are potentially suitable for monitoring population exposure to DPM. Likewise, Guadalupe is identified as a potentially suitable area for monitoring population exposure to DPM.

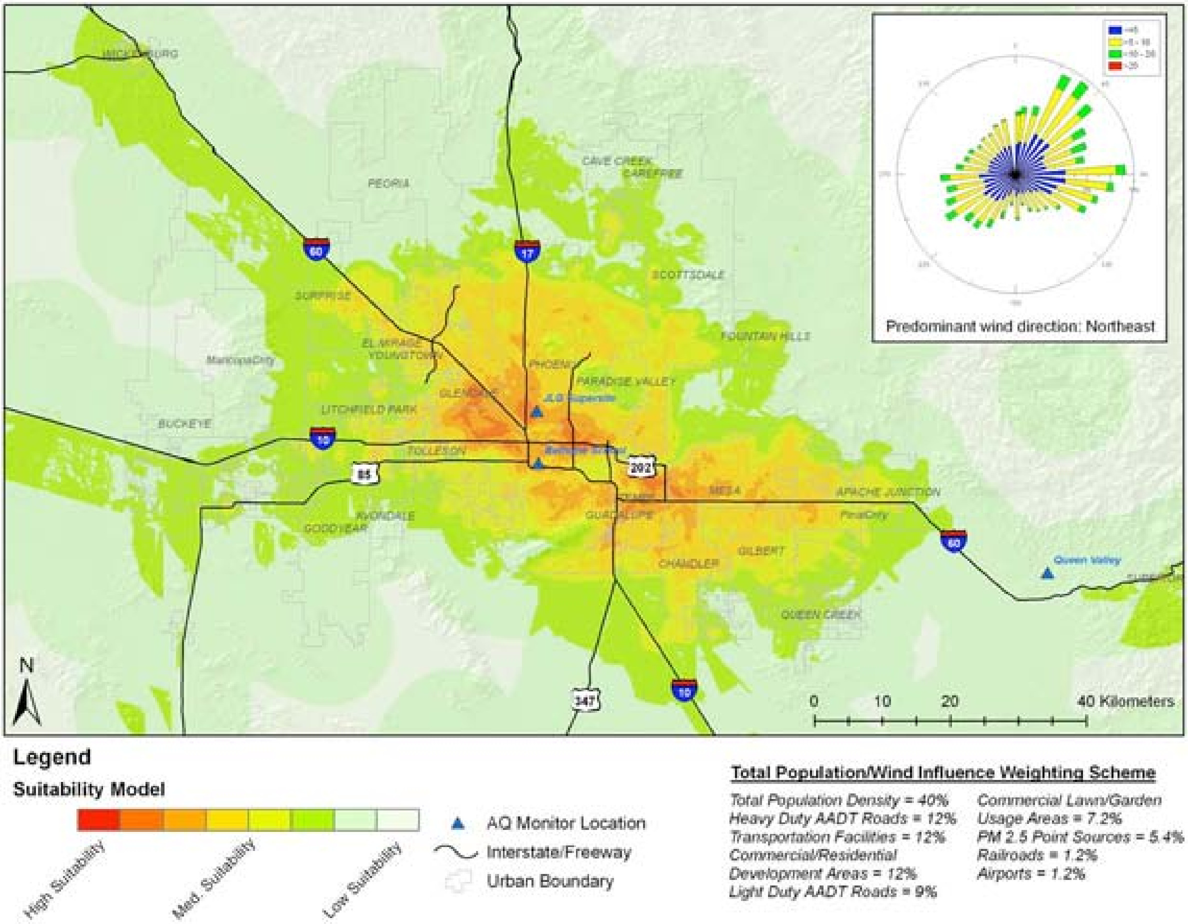

Figure 11. Total population suitability analysis accounting for meteorology

Figure 12 shows the results from the suitability model scenario 3 which accounts for sensitive population groups and meteorology. When sensitive population groups are weighted highest in the modeling scenario, suitability shifts to areas where there are greater populations of elderly people and children. For example, Mesa and Sun City contain the highest sensitive populations; thus, the region just southwest of Mesa and Sun City is indicated as potentially suitable for monitoring DPM in areas where sensitive populations live.

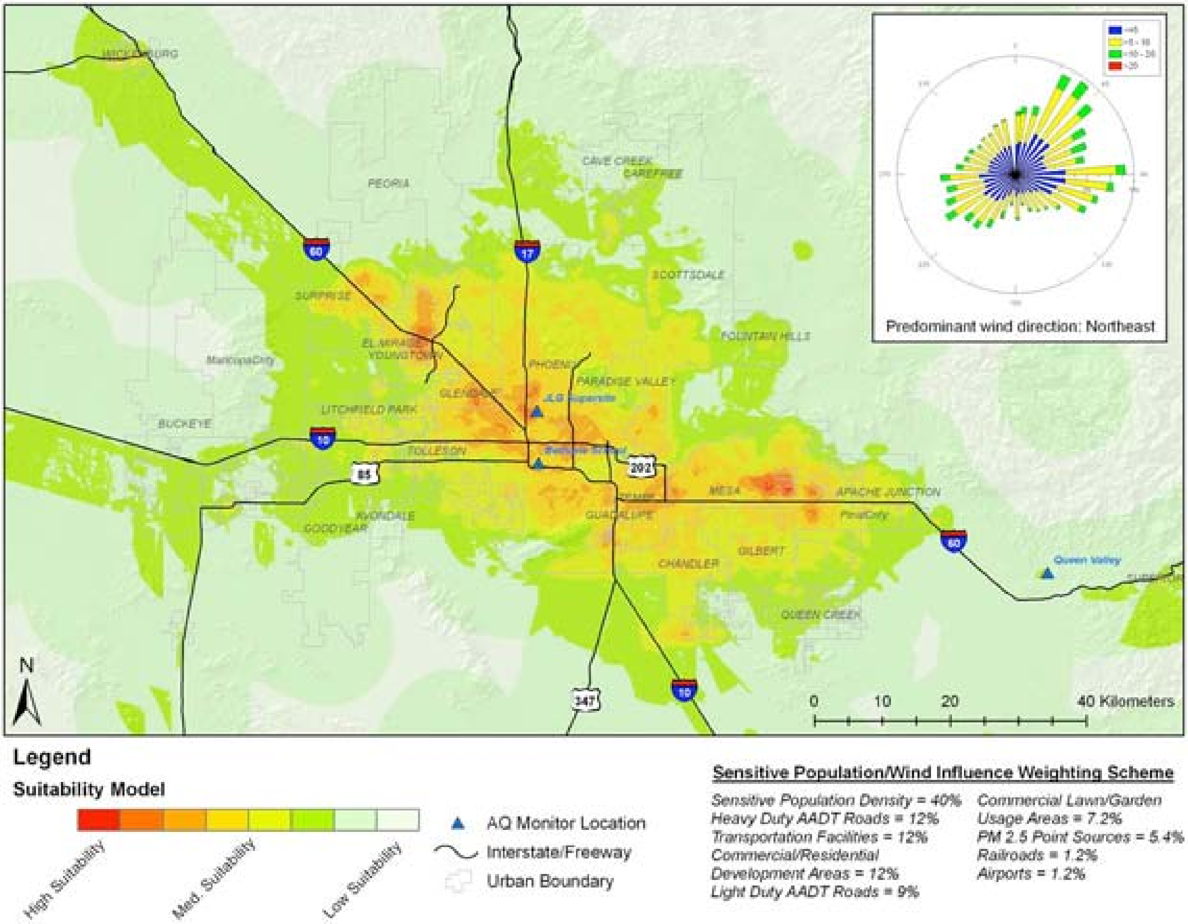

Figure 12. Sensitive population suitability analysis accounting for meteorology

CONCLUSIONS

The GIS-based Spatial Analyst tool was successfully applied to identify regions in the Phoenix area predicted to have high concentrations of DPM. Many sources of geographic data were used to develop the model. Areas of high DPM emissions were identified in the resulting suitability maps, as expected, along main truck routes, in highly industrial regions, and in areas of high construction activity. With the boom of construction in the Phoenix area, areas that have undergone substantial residential and commercial construction appeared on the resulting suitability maps as likely locations of DPM emissions. Incorporating meteorology into the suitability model significantly affected the results by introducing a southwestern shift in the areas identified as potentially suitable for monitoring DPM.

When the existing air toxics monitoring sites are overlaid on the resulting suitability maps, it appears that the two long-term air toxics monitoring sites located in central Phoenix—Bethune School and Phoenix Supersite—are well-located to monitor a mix of DPM emissions sources. However, when meteorology is accounted for, the areas identified as suitable shift to the southwest, consistent with the predominant southwesterly wind direction in Phoenix. It is important to note that the monitoring objectives for the Phoenix Supersite and Bethune School were not originally set to investigate DPM impacts.

When population density is considered, the existing two monitoring sites in central Phoenix are located in areas of high total population density. However, Mesa and Youngtown have high populations of sensitive groups (elderly people and children) and appear to be moderately influenced by DPM. These areas are potentially suitable for placing monitors in the future if the monitoring objective is to monitor DPM emissions in areas where sensitive groups reside. These areas were also identified in earlier work as highly suitable for monitoring benzene impacts on sensitive groups.[23]

This analysis demonstrates the utility and effectiveness of using spatial data with GIS tools to better understand urban-scale emissions patterns, their potential impact on population, and possible locations for placing monitoring sites to measure impacts of DPM. This analysis also demonstrates the importance of considering meteorology.

The results from these analyses should be considered preliminary and demonstrate the usefulness of the spatial suitability analysis techniques. Several other data types and analyses should be considered in future suitability analyses to enhance results:

- improved activity information for rail, heavy-duty diesel, and airport diesel emissions;
- continued assessment and refinement of surrogates for diesel construction;
- investigation of the relationship between EC and BC data in Phoenix and a comparison of EC and BC data to suitability model results; and
- investigation of seasonal variability in DPM sources (and meteorology) on the results.

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