Identifying Areas with Cumulative Impacts from Air Pollution in the San Francisco Bay Area

Version 2
March 2014

BAY AREA AIR QUALITY MANAGEMENT DISTRICT

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EXECUTIVE SUMMARY

This report describes updates to the Bay Area Air Quality Management District's (Air District's) methodology for identifying impacted communities. The updated methodology was used to create an updated map showing areas where air pollution's health impacts are relatively high in the San Francisco Bay Area. The updated map, like the current map of impacted communities, will be used to help prioritize and focus many of the Air District's activities. The maps of impacted communities help focus special studies and outreach and education programs. They help prioritize Air District activities that mitigate air pollution exposures from local emissions sources, activities such as grant and incentive funding, enforcement efforts, local and regional planning efforts, and the adoption of new and amended regulations.

Key differences between the previous methodology (version 1) and the methodology described here (version 2) include both updated inputs and modified methods. Specifically, version 2 uses more up-to-date representations of Bay Area air pollution levels than version 1; it includes more types of air pollutants; and it sets different criteria for defining impacts. The version 2 methodology is based on an approach that estimates health impacts from air pollution levels: cancer risk from exposure to toxic air contaminants (TAC) and increased mortality rates and increased health costs from exposure to fine particles ($PM_{2.5}$) and ozone in outdoor air.

The version 2 methodology is based on quantitative assessments of air pollution impacts on health. In applying version 2, rather than using indirect proxies for health impacts, the Air District estimated health impacts directly by considering air pollution levels and population vulnerabilities. Rather than using socioeconomic factors to represent vulnerabilities however, the Air District used health records to represent them. In other words, following the version 2 methodology, health impacts were determined both by pollution levels and by existing health vulnerabilities in a community. Areas with higher air pollution levels and worse health outcomes, for diseases affected by air pollution, were identified as impacted. It is important to note that relatively poor health in a community can be due to multiple causes, other than air pollution, but it leads to greater sensitivity to air pollutants.

Income, education level, and race and ethnicity data were not used to represent population vulnerabilities in version 2. But, although socioeconomic factors were not used, there is a clear correlation between socioeconomic disadvantage and racial minorities and the impacted communities identified by this method. Demonstrating this correlation in was an important step in the evaluation of the updated methodology.

Application of the version 2 methodology resulted in an updated set of impacted communities (Figure ES1): Richmond/San Pablo; eastern San Francisco, including Treasure Island; San Jose; western Alameda County; Concord; Vallejo; and Pittsburg/Antioch. Version 2 and version 1 communities are similar, but there are some important changes:

- The Redwood City/East Palo Alto area is not included in the version 2 map;
- Two communities, Vallejo and Pittsburg/Antioch, have been added in the version 2 method; and
- Several impacted areas were expanded: the eastern San Francisco area now includes Treasure Island; the San Jose area was expanded to the west; the western Alameda County area was expanded to the bay coast and now includes the City of Alameda; and the Concord area was expanded to the north.

The addition of two communities and the expansion of others in the updated map do not imply that air pollution in the Bay Area is getting worse. In fact, air pollution levels have been dropping in nearly all Bay Area communities. The addition and expansion of areas is due to the added consideration of new pollutants, primarily fine particulate matter, in the version 2 method.

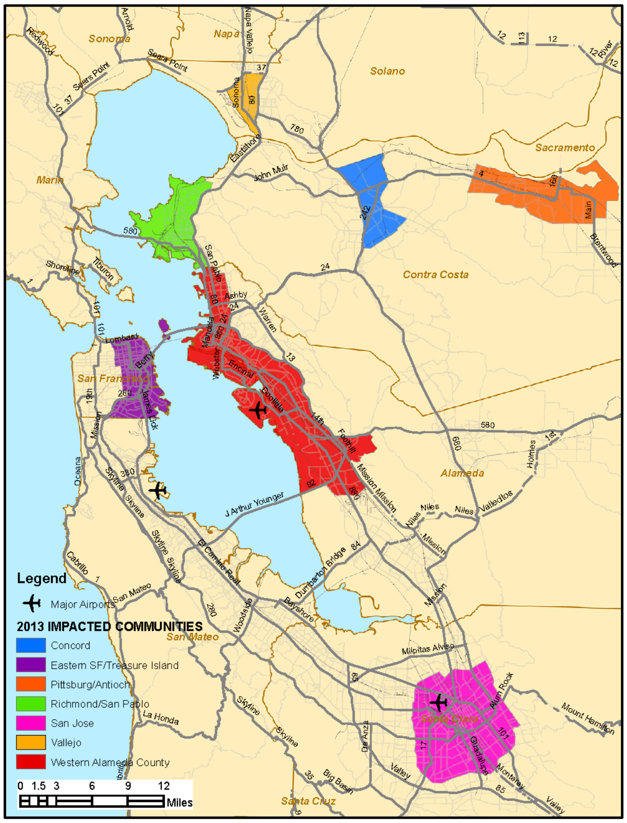

Figure ES1. Revised (version 2) impacted communities.

This analysis provides a "macro-scale" identification of impacted communities. Communities identified as impacted share broad similarities that indicate a greater chance of individual risks from air pollutants. While a macro-scale analysis is appropriate for focusing Air District resources, it is not useful for project-level planning, where a more local-scale analysis is required.

Throughout the process of developing the version 2 methodology, Air District staff was assisted by an ongoing and informative process of discussion, feedback, and review from members of the Community Air Risk Evaluation (CARE) Task Force. More information on the CARE Task Force, the CARE program, and the uses for maps of impacted areas is available in a CARE program summary report.[1]

INTRODUCTION

The Bay Area Air Quality Management District (Air District), the regional agency responsible for air pollution control in the San Francisco Air Basin (Bay Area), is committed to improving air quality for all Bay Area residents. This commitment, coupled with the efforts of state and federal partner agencies, has resulted in significant air quality improvements throughout the Bay Area, as indicated by measurement trends at regional air monitoring locations.[2] Yet, in spite of significant air quality improvements, there are still locations within the Bay Area where air pollution levels remain relatively high, especially near localized emissions sources. Moreover, while pollution levels are dropping in nearly all parts of the Bay Area, the Air District's measurement sites still sometimes record episodes of fine particulate matter and ozone at levels above state and federal standards.

Some Bay Area communities suffer poorer health and may be more vulnerable to the adverse health consequences of air pollution than others. Multiple studies have shown that low-income communities, communities with higher populations of racial or ethnic minorities, communities with combined stressors such as noise, crime, and under-employment have less access to health care, elevated stress levels, and reduced resiliency to the added health burden of air pollution.[3,4] Moreover, communities whose residents are most vulnerable frequently contain more high-emissions source areas.

In 2004, the Air District initiated the Community Air Risk Evaluation (CARE) program to intensify efforts to reduce air pollution in areas with greatest air pollution burdens and with most vulnerable populations. The goals of the CARE program parallel recent California and federal legislation[5,6] that require their respective environmental agencies to address the disproportionate adverse health effects pollution can have on minority and low-income populations. Through the CARE program, the Air District has worked to identify communities most adversely impacted by air pollution. Once a community is identified as impacted, the Air District focuses grants, enforcement programs, local-scale studies, and other activities to help reduce pollution exposures within the community.

Through the CARE program, an initial effort completed in 2009 identified areas as impacted by air pollution if they had relatively high emissions of toxic air contaminants, relatively high exposures of youth and seniors to toxic air contaminants, and relatively high levels of poverty. This report presents an updated methodology for identifying communities impacted by air pollution. The new methodology considers multiple air pollutants, as well as local mortality and morbidity health data.

BACKGROUND

Air pollution can cause health effects ranging from shortness of breath, coughing and chest pain to heart attacks, lung cancer and even early death. In the San Francisco Bay Area, the main pollutants of concern are fine particles ($PM_{2.5}$), carcinogens (most notably diesel exhaust), and ozone. Studies of long-term exposure to fine particles have found links to cardiopulmonary mortality[7] and strong associations with heart disease. Research on health effects suggests that exposures to fine particles can lead to inflammation which in turn causes exacerbations of lung disease and of increased blood coagulation.[8-10] Studies of worker exposures to diesel exhaust found increased risks of lung cancer.[11] Long-term exposures to ozone have been linked to both mortality and lung diseases[12] but at the concentrations found in the Bay Area these impacts are much less than those from $PM_{2.5}$.

Through efforts by the Air District, California Air Resources Board, and US EPA, dramatic reductions in air pollution have been achieved that have led to better health and longer life for Bay Area residents.[13] However, in spite of regional air quality improvements, many communities are still exposed to unhealthy levels of air pollution.

In 2008 through the Air District's CARE program, researchers began developing an approach to identify areas that are disproportionally impacted by air pollution. The objective was to identify specific communities where there were relatively high levels of air pollution, as well as concentrated vulnerable populations. Emission reduction efforts in these areas, through various agency programs, were then given priority. In 2009, the Air District developed a map depicting "impacted communities" – geographic areas in the region that have high pollution levels, as indicated by emissions and concentrations of carcinogenic toxic air contaminants (TAC), and vulnerable populations, as indicated by high percentages of youth and senior populations and low-income families.

Since 2009, additional methods and tools have become available. The Environmental Justice Screening Method (EJSM) was developed to assess health risks in vulnerable populations in California.[14] The California Environmental Protection Agency's Office of Environmental Health

Hazard Assessment recently developed a methodology, CalEnviroScreen, designed to assess the aggregate impacts of pollution on California's communities.[15] CalEnviroScreen uses environmental, health, and socioeconomic data to rate various communities throughout California, to allow for regional comparisons. US EPA released the Environmental Benefits Mapping and Analysis Program (BenMAP) tool that allows users to estimate health impacts and associated costs from increments in air pollution.[16]

The method used by the Air District in 2009 to identify impacted communities, the EJSM, and CalEnviroScreen are all forms of screening methods. Screening methods use factors such as pollution levels, proximity to pollution sources, and socioeconomic population characteristics to identify areas where, based on associations found in previous studies, there may be health impacts. Screening methods are used to rank areas based on potential impacts, but they do not quantify the impacts. In contract, BenMAP is an assessment methodology. An assessment methodology does quantify impacts. Specifically, BenMAP uses correlations found in epidemiological studies to quantify specific health impacts of changes in pollution levels.

This report describes updates to the Air District's methodology. Key differences between the 2009 method (version1) and the approach described here (version 2) include both updated inputs and modified methods. Compared to version 1, version 2:

- **Used more current data**, including air quality inputs. Version 1 used potential cancer risk from air pollutants estimated based on emissions in 2005. Since air pollution levels have dropped significantly in the Bay Area since 2005, version 2 uses the most up-to-date air quality inputs available, 2010 or later.
- **Included additional air pollutants.** In addition to toxic air contaminants considered in version 1, version 2 also included $PM_{2.5}$ and ozone.
- **Used new methods.** Version 2 used health outcomes estimated from air pollution levels to identify impacts, following an approach similar to that used in BenMAP.

The methodology followed for version 2 is more like an assessment method than a screening method. As described in the following section, rather than using indirect proxies for health impacts, version 2 estimates rates of health outcomes directly from air pollution exposures. Rather than using socioeconomic factors to represent vulnerabilities, version 2 uses health records to represent them.

The Air District favors a more quantitative approach based on health outcomes because this ties the identification of impacted areas more directly to the essential issue of health impacts due to poor air quality.

A NEW METHODOLGY FOR IDENTIFYING IMPACTED COMMUNITIES

Process, Feedback, and Review

In developing an updated methodology for identifying impacted communities Air District staff were assisted by an ongoing and informative process of discussion, feedback, and review from members of the Community Air Risk Evaluation (CARE) Task Force and others. Proposed updates to the methodology were discussed at length at four Task Force meetings and feedback received greatly influenced its development.

In June of 2012, the CARE Task Force convened a Technical Workshop on methods and screening tools for identifying impacted communities. At that meeting, Air District staff presented the version 1 method and discussed plans for updates; Dr. George Alexeeff, Director of the Office of Environmental Health Hazard Assessment at Cal/EPA, presented progress toward the CalEnviroScreen method; Dr. Rachel Morello-Frosch, Associate Professor at the University of California at Berkeley in the School of Public Health, presented an overview of the EJSM and benefits of Community Participation; and Dr. Rajiv Bhatia, Director of Environmental Health in the San Francisco Department of Public Health, presented work in the City and County of San Francisco on identifying and protecting communities from urban air pollutants. These presentations and the ensuing discussions were pivotal in shaping the Air District's updated method.

Guidance from Dr. Jane Martin, Epidemiologist Manager with the Alameda County Public Health Department and member of the Air District's CARE Task Force, and her staff provided critical guidance on obtaining and using health records. Expert review from Dr. Paul English, Branch Science Advisor with the Environmental Health Investigations Branch of the California Department of Public Health, provided useful feedback on the use of health data and stimulated ideas for future work.

Methodology Overview

To update maps of Bay Area communities disproportionally impacted by air pollution, the Air District has developed an updated methodology (version 2). The version 2 methodology evaluates health impacts from air pollution in the Bay Area. To determine health impacts from air pollution, the version 2 methodology determines where air pollution concentrations are relatively high and it determines where residents are particularly vulnerable. The version 2 methodology does not rely on socioeconomic information to determine vulnerability; instead, it uses recent health records to determine mortality rates and rates of illnesses aggravated by air pollution.

As shown in Figure 1, the version 2 methodology inputs pollutant concentrations of TAC, $PM_{2.5}$, and ozone to assess three kinds of health impacts. To assess the impacts of concentrations of TAC, the version 2 method used cancer-risk factors for TAC developed by Cal/EPA[17] to estimate an increase in cancer risk from air pollution. To assess health impacts of $PM_{2.5}$ and ozone concentrations, version 2 follows the approach of BenMAP,[16] developed by US EPA, and numerous studies of adverse health outcomes due to poor air quality.[18-21]

BenMAP uses published health studies to predict an increase in health impacts with increments in pollutant concentrations using two key sets of inputs:

- Air pollution levels above background, and
- Health records, including baseline rates of mortality, emergency room visits, and hospital admissions within a community.

This approach yields increased rates of non-accidental mortality and increased hospital admissions and emergency room visits for several cardiovascular and respiratory causes. The increased rates of hospital admissions and emergency room visits were combined by tallying the cost associated with each additional incident.

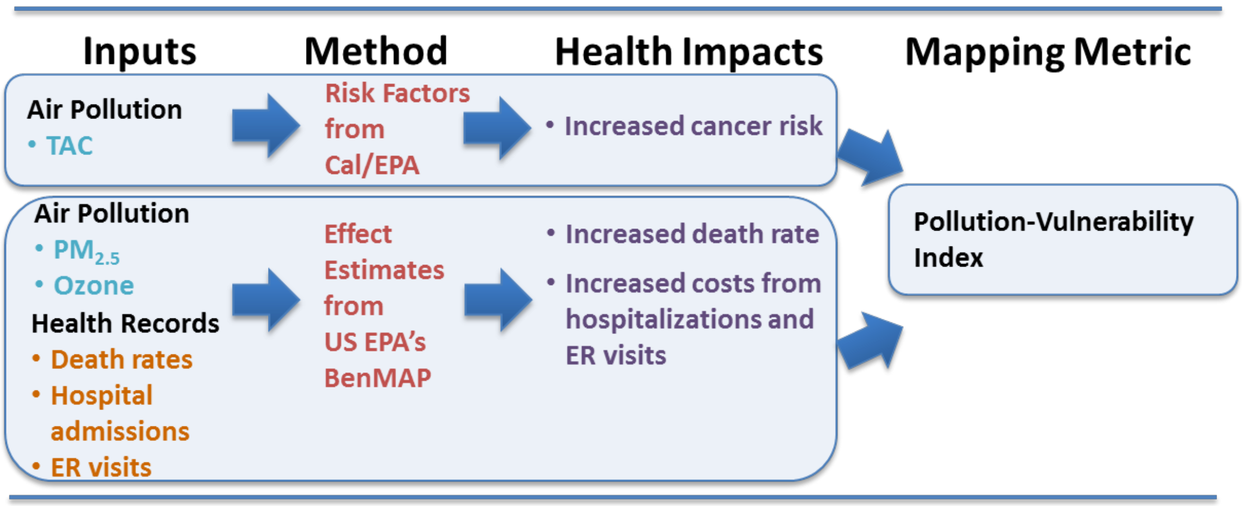

Figure 1. The version 2 method inputs air pollution levels and health records to estimate health impacts from air pollution in the Bay Area.

Mortality rates, hospital admissions, and emergency room visits (health records) were used to determine population vulnerabilities in the assessment of health impacts from $PM_{2.5}$ and ozone. Figure 1 shows that both air pollution concentrations and health records were used as inputs in the version 2 method.

Health impacts were aggregated into a single metric that can be used for mapping areas of highest overall impact. The metric used to aggregate health impacts is the *pollution-vulnerability index*. The pollution-vulnerability index, described in more detail in the *Methodology Description*, is the final result of the process shown in Figure 1.

Figure 2 illustrates how using a BenMAP approach predicts health impacts using both air pollution levels and baseline health records. An increment in an adverse health outcome (health impact, left box) from air pollution depends not only on a concentration-response fraction determined by pollution levels (center box) but also on the baseline rate of the health outcome (right box). That is, the health impact from air pollution depends in part on the existing health of a community. By using zip-code level baseline rates, derived from health records, the version 2 method accounts for existing disparities in health outcomes among Bay Area communities. For example, an increased death rate is predicted from $PM_{2.5}$ levels above background in a community, with the increase depending on not only on $PM_{2.5}$ concentrations but also on the baseline death rate of the community. By this method, if two communities have the same $PM_{2.5}$ concentrations, but one has a higher non-accidental mortality rate, the one with the more vulnerable population, as reflected by the higher baseline mortality rate, will have a larger increment in mortality from $PM_{2.5}$ concentrations.

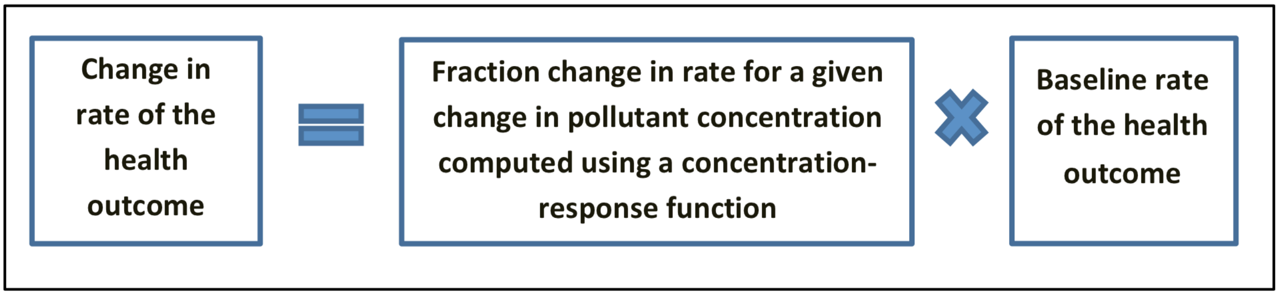

Figure 2. Illustration of the BenMap approach: an increment in an adverse health outcome (left text box) depends not only on pollution levels (center text box) but also on the baseline rate of the outcome (right text box) determined from health records.

To assess which communities are most impacted, version 2 ranks areas by the estimated impact of carcinogens, $PM_{2.5}$, and ozone on health. In summary, version 2 impacts are determined both by pollution levels and by existing health vulnerabilities.

Methodology Description

Further description of the methodology follows in this section, along with discussion of the inputs used and processing required. Because health records used for establishing baseline rates were available by zip code, Bay Area zip codes were chosen as the spatial unit of this analysis. The discussion below explains how zip codes were processed and, in some cases combined; how estimates of air pollution levels were derived for the Bay Area and mapped to zip codes; what mortality and morbidity records were used; and how these inputs were combined to create maps of areas of greatest air pollution impact. The section ends with a description of supporting data and analyses used to understand population characteristics of areas identified as impacted.

Zip Code Areas

Because mortality and morbidity (hospital admissions and emergency room visits) records are available at the zip code level, zip codes were chosen as the spatial unit of analysis. Zip codes from the mortality and morbidity data were matched with populated zip codes from the 2010 Census. All zip codes with less than 2,000 people were aggregated with their neighbors into *zip code areas*. See Appendix A for details.

Air Pollution Concentrations

Air pollution concentrations, critical inputs for the version 2 method, were derived from a combination of modeling and measurements. $PM_{2.5}$ and carcinogenic TAC concentrations (benzene, 1,3-butadiene, formaldehyde, acetaldehyde, and diesel particulate matter) were obtained from gridded model runs: $PM_{2.5}$ from the Community Multi-Scale Air Quality (CMAQ) model for a representative set of days in 2010 and 2011; carcinogenic TAC from the Comprehensive Air Quality Model with Extensions (CAMx) for 2015. Both models divided geographic area into grids and yielded estimates of $PM_{2.5}$ or TAC in each grid cell. CMAQ particulate matter modeling used grid cells with horizontal dimensions of 4 km; CAMx toxics modeling used grid cells with 1 km horizontal dimensions. (PM modeling required more computer time to complete relative to the toxics modeling, so coarser grids were used to help speed the computations.) Peak $PM_{2.5}$ model values were adjusted to more closely match observations for the same period when significant differences were found. In order to combine the modeled toxic compounds into a single parameter (cancer risk), concentrations of TAC were multiplied by their corresponding unit cancer risk values[17] and summed.

TAC and $PM_{2.5}$ were mapped from modeling grid cells to each zip code area. The mapping from grid cells to zip code areas first interpolated modeling results to census blocks within zip code areas. Then, concentrations for the census blocks were averaged within each zip code area using population weighting. Population weighting was used to provide an average estimate of concentrations within a zip code area that best represents what people in the zip code are exposed to. For example, in a large zip code area there can be changes in pollutant concentrations across the zip code. Rather than uniformly averaging concentrations within the zip code, higher weight is given to concentrations in areas with more people. Population data were derived from the 2010 Census.

Ozone concentrations in each zip code area were estimated from data measured at Bay Area monitoring sites. Daily maximum 8-hour ozone for 2010 and 2011 was interpolated to census blocks using inverse distance weighting and then averaged within each zip code area using population weighting. Ozone increments above background (40 ppb) were averaged over the two-year period. See Appendix B for details on determining pollution concentrations and on mapping concentrations to zip code areas.

Mapping Pollutant Concentrations and Cancer Risk

Figure 3 shows cancer risk and pollutant concentrations mapped to zip code areas. Cancer risk per million exposed (Figure 3a) were estimated from modeled TAC concentrations; annual-average $PM_{2.5}$ concentrations (Figure 3b) were estimated from a combination of modeling and measurements; and 8-hour ozone concentrations above background (Figure 3c) were estimated from measurements. Bay Area cancer risk and $PM_{2.5}$ concentrations are highest in the region's more urbanized areas, reflecting traffic density and other sources in the Bay Area's core. But while cancer risk estimates are strongly focused in the urban core where diesel particles are most concentrated, $PM_{2.5}$ concentrations are also high further downwind, generally east of the urban center. The pattern of $PM_{2.5}$ concentrations is more widely dispersed partly because $PM_{2.5}$, in addition to being directly emitted, also has a significant secondary component—gaseous precursor pollutants combine and condense to form particles—that extends further downwind. Ozone concentrations are highest downwind of urban centers, especially during the summer months. Ozone is entirely secondary, formed from precursor pollutants that are transported downwind before reacting to produce peak ozone.

Mortality and Morbidity Data

Other critical inputs for the version 2 method were mortality data and morbidity data (hospital admission and emergency room visits). Mortality data for Bay Area zip codes were extracted from statewide death records for years 2008, 2009 and 2010, the most recent data available at the time of this analysis. Counts of non-accidental mortality,[22] obtained for each zip code area and for ten age brackets, were averaged across the three years of data. Hospital admission and emergency room visit counts were obtained from the Office of Statewide Health Planning and Development (OSHPD) for health outcomes related to air pollution. These counts were obtained for each Bay Area zip code, for the same age brackets as the mortality data, and for the most recent years available: in this case 2009, 2010, and 2011. Morbidity data were also averaged across the three years for which data were obtained.

Table 1 lists health outcome data used in this analysis by principal diagnoses, or illnesses, along with corresponding international classification of diseases (ICD-9CM) codes.

Table1. Morbidity health outcome data obtained by principal diagnoses and classification codes.

Illnesses	ICD-9CM Codes
COPD Hospital Admissions	490-496
Pneumonia Hospital Admissions	480-486
Myocardial Infarction (MI, Heart Attack) Hospital Admissions and Emergency Room Visits	410
Cardiovascular Hospital Admissions (less MI)	390-429 (except 410)
Asthma Emergency Hospital Admissions and Emergency Room Visits	493.01-493.99
Asthma Hospital Admissions	493.01-493.99
Hospital Admissions for Respiratory Diseases	460-519

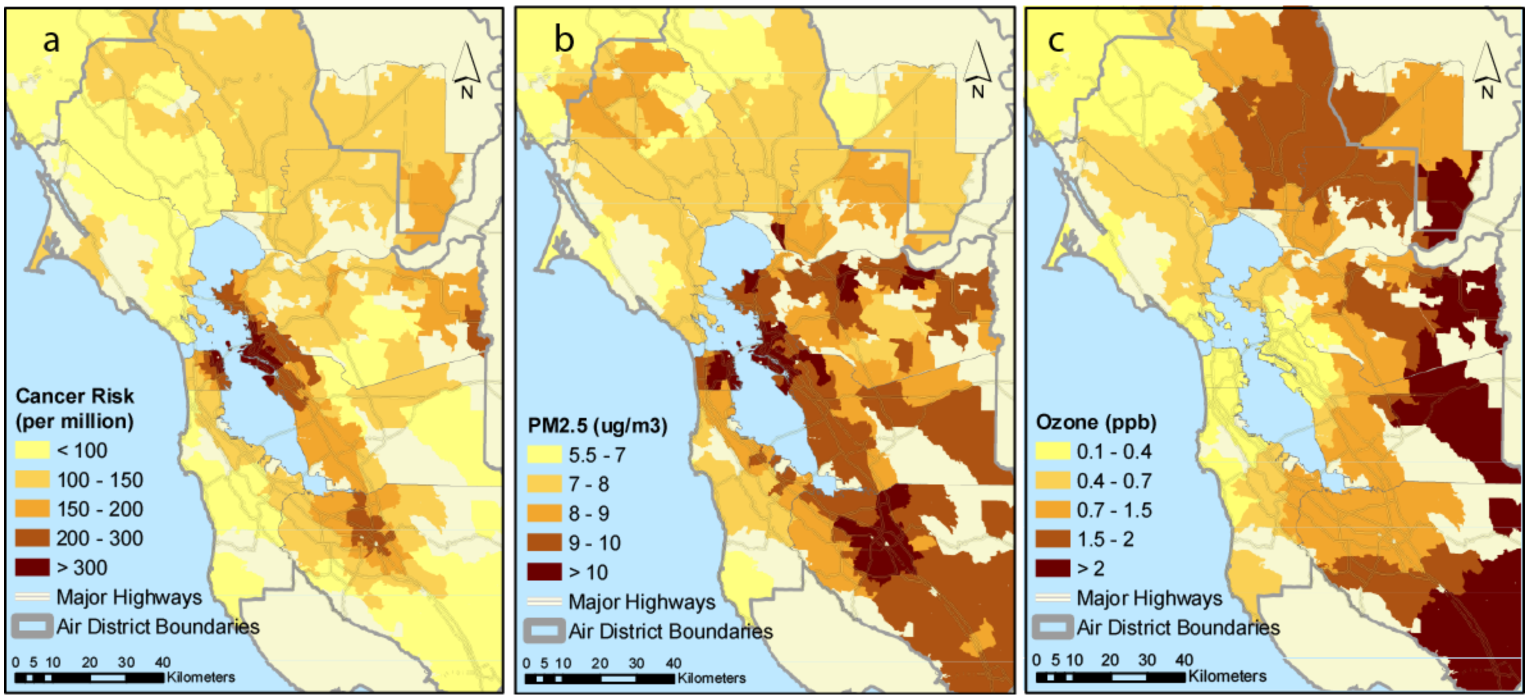

Figure 3. Cancer risk and air pollution levels mapped to zip code areas: (a) cancer risk from air toxics, (b) annual $PM_{2.5}$, and (c) mean 8-hour ozone above background.

Estimating Health Impacts from Air Pollution

To estimate the effect of $PM_{2.5}$ and ozone on non-accidental mortality rates and morbidity costs, the version 2 method applied concentration-response functions from BenMAP. We assumed that the dose-response relationship in health effects applied to concentrations above background, defined as 40 ppb for ozone and 5 μg/m3 for $PM_{2.5}$. The pollutant impacts on non-accidental mortality rates and morbidity endpoints were estimated for each zip code area. The pollutant-impacted morbidity rates were combined into a pollutant-impacted morbidity cost. See Appendix C for details.

To evaluate the health impacts from $PM_{2.5}$ and ozone, the version 2 method required establishing baseline rates for each health end point. The rates were computed using zip code specific data on mortality, hospital admissions and emergency room visits for all age brackets. These rates were adjusted to the age distribution of the Bay Area. Hospital and emergency room visit endpoint rates were combined by multiplying each rate times the per-visit cost and summing across the endpoints to find the *morbidity cost*. Information on per-visit costs was derived from BenMAP documentation. Costs reflect estimated total social cost (lost wages, impact on family) as opposed to the cost of health care only. The same per-visit costs were used across the Bay Area so that differences in health-care costs were not a factor.

To evaluate the health effects from carcinogenic toxics, we used the cancer risk estimate for each zip code area, expressed in terms of excess risk of cancer per person exposed over a presumed 70-year lifetime. The method assumed that TAC concentrations remained constant at 2015 levels during the life-time of exposure. This is likely a conservative assumption for risk levels looking ahead since TAC concentrations have been trending strongly downward in the Bay Area in recent years. See Appendix D for details on the calculation of cancer risk.

Three components were considered in estimating health impacts from air pollution: increased mortality rates from air pollution, increased per capita costs of morbidity from air pollution, and increased cancer risk from air pollution. The mortality and morbidity increments accounted for the base mortality and morbidity rates, respectively, in each zip code area. The cancer risks were calculated independently of base rates. The three components were each ranked in order of increasing pollution health impact and the three ranks were summed for each zip code to form a *pollution-vulnerability index*, which was expressed as a percentage of the highest sum.

Mapping Emissions

Reducing emissions of air pollution is the primary focus of mitigation strategies to reduce impacts. Locations of high emissions source areas were therefore considered when forming boundaries to mark the extent of impacted communities.

To identify high emission source areas, the analysis included gridded emissions estimates from the 2015 TAC modeling (1km grids) and the 2010 PM modeling (4 km grids). TAC modeling provided gridded emissions of carcinogenic toxic compounds; PM modeling provided direct emissions of $PM_{2.5}$, and precursor emissions of both $PM_{2.5}$ and ozone. Precursor emissions included oxides of nitrogen (NO_x), sulfur dioxide (SO_2), and volatile organic compounds (VOC).

Emissions of primary PM (Figure 4a) tend to be more broadly distributed than cancer-risk weighted toxic emissions (Figure 4b), which also contributes to the broader distribution of $PM_{2.5}$ concentrations relative to cancer risk. Whereas the distribution pattern of cancer risk-weighted emissions closely follows that of diesel PM emissions—along major roadways and in the urban center—primary $PM_{2.5}$ emissions arise from diesel combustion but also from many other sources of combustion, such as residential wood-burning and industrial sources. The pattern of NO_x emissions (Figure 5a) is similar to that of $PM_{2.5}$, reflecting the similarity of sources, mostly combustion related. The pattern of SO_2 emissions (Figure 5b) is distinctly different, an indication of the dominant sources: ships, refineries, and other industrial facilities. The pattern of VOC emissions (Figure 5c) loosely resembles that of primary PM and NO_x, since combustion is an important source of VOC, but is more evenly distributed throughout the Bay Area, reflecting the importance of evaporative VOC emissions from a broad variety of sources.

Gridded modeling emissions of the compounds shown in Figures 4 and 5 were used to form an *emissions index* that combined all emissions into a single parameter. Carcinogenic compounds were multiplied by their cancer risk potency, summed, and then converted to a percentage of the maximum emissions grid to form one component of the emissions index. Direct emissions of $PM_{2.5}$ were converted to a percentage of the maximum $PM_{2.5}$ emissions grid to form a second component. Precursor emissions were each normalized by their respective maximum emissions grid, summed, and converted to a percentage of the maximum sum to form a third component. The three components—cancer risk weighted TAC, direct $PM_{2.5}$, and combined precursors—were summed to form the emissions index.

Identifying Impacted Communities

To identify communities most impacted by air pollution, the top 15% of the pollution-vulnerability index was mapped and examined for all the Bay Area zip code areas. In mapping the various indices, only populated portions of the zip code areas are shown. Populated areas were identified by land-use categories other than rangeland and other open space.

As described above, the pollution-vulnerability index includes impacts from toxic carcinogens and from death and illness from fine particles and ozone. It also accounts for the underlying (zip code level) health of a community's population for many health endpoints exacerbated by air pollution. The top 15% of the pollution-vulnerability index was plotted with the top 25% of the emissions index and boundaries were formed around communities with the highest impacts using coastlines, freeways and major roadways, and county boundaries as guides. The emission index helped to identify potentially important source areas and was considered in selecting boundaries for each area.

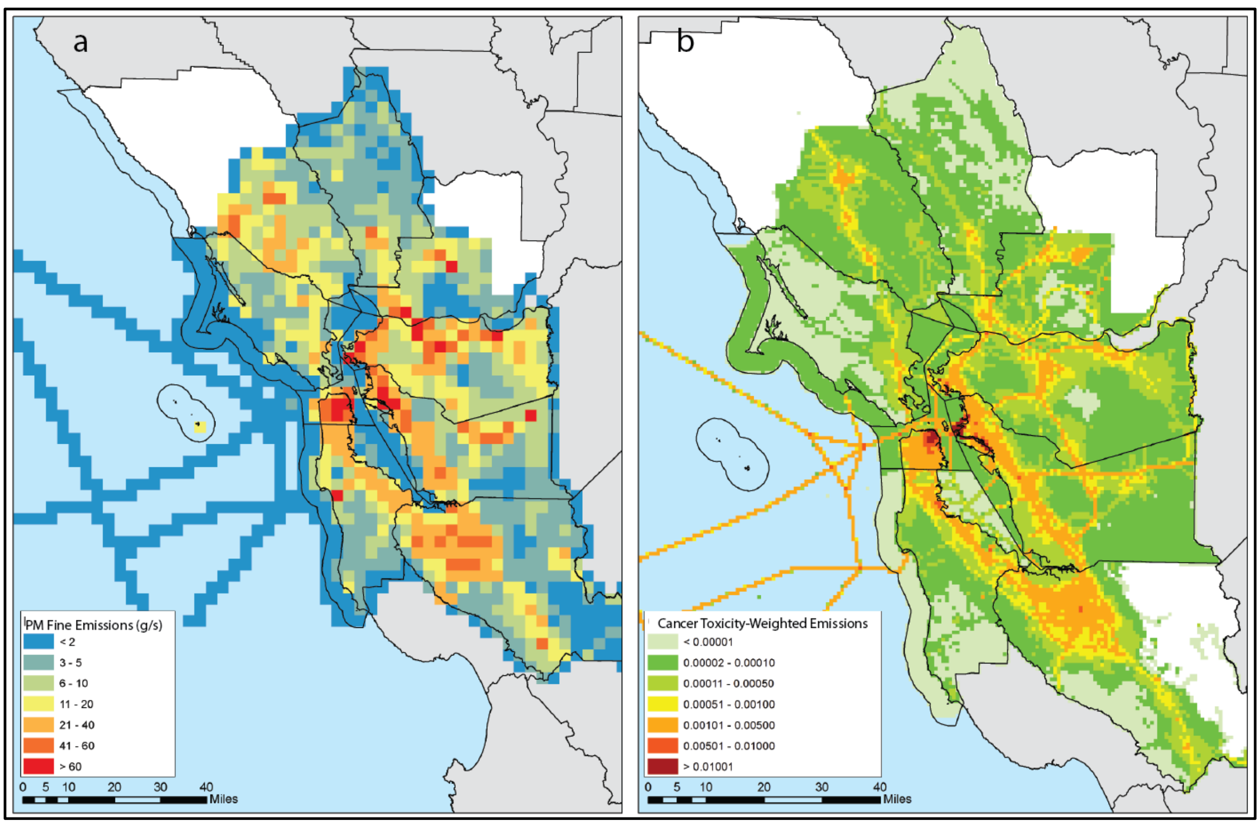

Figure 4. Emissions of (a) direct $PM_{2.5}$ and (b) carcinogenic toxic air contaminants weighed by cancer toxicity.

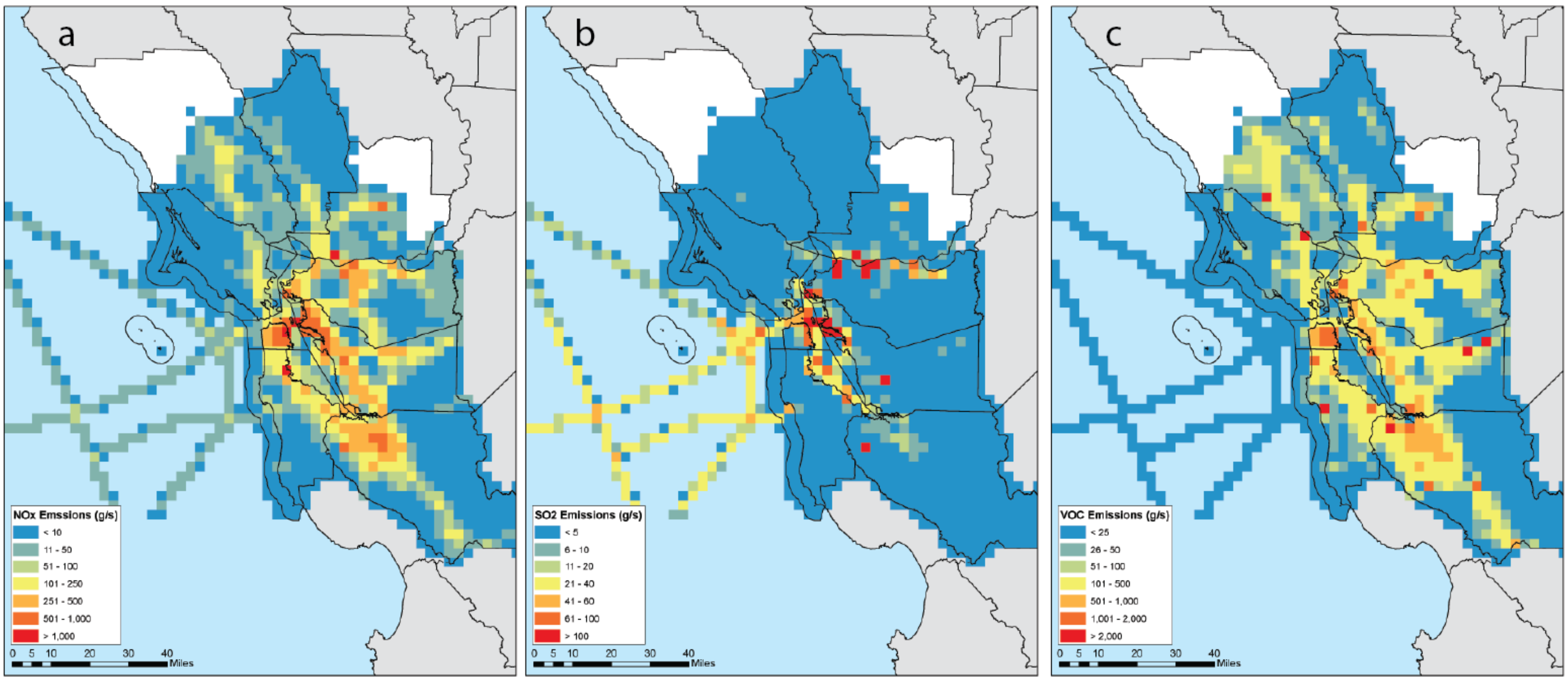

Figure 5. Precursor emissions of (a) nitrogen oxides (NO_x), (b) sulfur dioxide (SO_2), and (c) volatile organic compounds (VOC).

Additional Analyses and Comparisons

Socioeconomic Data

Socioeconomic data were not used to identify impacted areas in the version 2 method. However, once impacted areas were identified, these data were used to investigate population characteristics within them. Data on race, income, and education were obtained from the US Census Bureau. Block group population totals from the 2010 Census were obtained for the major ethnic groups and aggregated to each zip code area. Data on income and education were obtained from the American Community Survey for 2006-2010, by block group and averaged for each zip code area.

Comparison indices

To help evaluate the relative importance of air pollution versus base rates of mortality and morbidity costs in the pollution-vulnerability index, two additional indices were developed. One index, a *pollution index*, was formed following steps used to develop the pollution-vulnerability index except that, to estimate impacts from $PM_{2.5}$ and ozone, a single set of average rates for the whole Bay Area was used instead of using base mortality and morbidity rates specific to each zip-code area. The pollution index (with Bay Area rates) only depends on pollution levels and not the population health in a zip code area.

A second index, a *vulnerability index*, was formed by ranking non-accidental mortality rates and morbidity costs from health records for each zip code area for the same health endpoints as were estimated using BenMAP. The vulnerability index is the sum of these two ranks, and expressed as a percentage of the maximum sum. Because it is developed using health records, the vulnerability index reflects underlying population health. Population health is affected by air pollution, but also, largely, by socioeconomic and behavioral factors.[23]

RESULTS

Mapping Air Pollution Impacts

The pollution-vulnerability index (PVI, Figure 6) aggregates the health impacts from toxic carcinogens, $PM_{2.5}$, and ozone. Existing local health outcomes also influence the PVI because air pollution effects were calculated using records of base rates of mortality, hospitalizations, and emergency room visits for each zip code area. The PVI is high where $PM_{2.5}$ concentrations and cancer risk are relatively high, but it is also high where the population currently has higher mortality rates and higher rates of illnesses that can be exacerbated by air pollution. Ozone health impacts were included but were substantially less than those of $PM_{2.5}$ for Bay Area pollution levels. $PM_{2.5}$ accounted for about 90% of the health costs from hospitalizations and emergency room visits compared to about 10% from ozone. $PM_{2.5}$ accounted for about 95% of the increase in mortality rates compared to about 5% from ozone.[*]

Figure 6 shows PVI values ranging from 0 to 100, in increments of 10. The highest PVI values indicate the areas with the greatest health impacts from air pollution. To show health impacts where people live, Figure 6 maps PVI only in portions of zip code areas that are populated.

Identifying Impacted Communities

Figure 7 shows the revised map of impacted communities produced by the version 2 methodology. The pollution-vulnerability index (PVI) was used identify impacted areas. The top 15% of PVI values was mapped to identify areas with the greatest health impacts from air pollution. Coastal and county boundaries along with major roadways were used to form the actual boundaries. The top 25% of the emissions index was also mapped in Figure 7 as an aid in selecting the specific roadways to use in mapping the boundaries of impacted areas. The method selected roadways and other geographic features to include the highest 15% PVI areas and to include adjacent emissions that were judged likely to contribute to air pollution in these areas.

Using the top 15% of PVI values resulted in boundaries that covered an extent that was similar to, but larger than, the version 1 maps. The version 2 maps covered about 5% of the land area within the Air District's boundaries and about 29% of the population (2.2 million, based on the 2010 US Census). The version 1 maps covered 3% of the land area and 24% of the population (1.8 million). Cal/EPA's CalEnviroScreen documentation[15] has presented a similar range of percentages, between 5% and 15%, for identifying the most impacted areas in California. The top 25% of emissions was used to expand the areas ournt the top PVI values and target emissions that may contribute to the highest impact areas.

[*] These findings are consistent with those of the Air District's 2010 Clean Air Plan,[2] which provided a multi-pollutant analysis of the Bay Area's air pollution impacts.

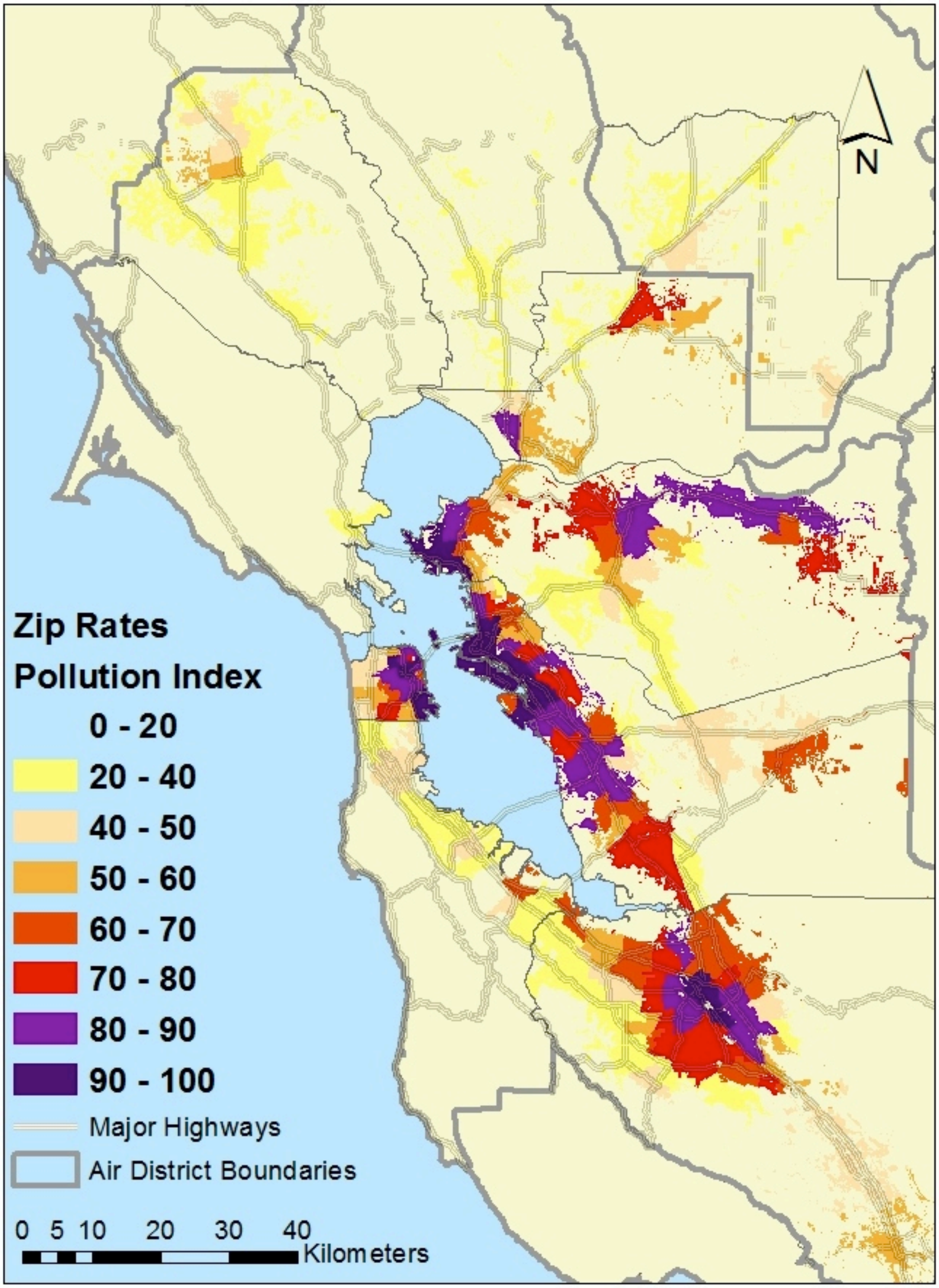

Figure 6. The pollution-vulnerability index uses information on air pollution levels and health outcomes for each zip code area. Only populated portions of each zip code area are shown.

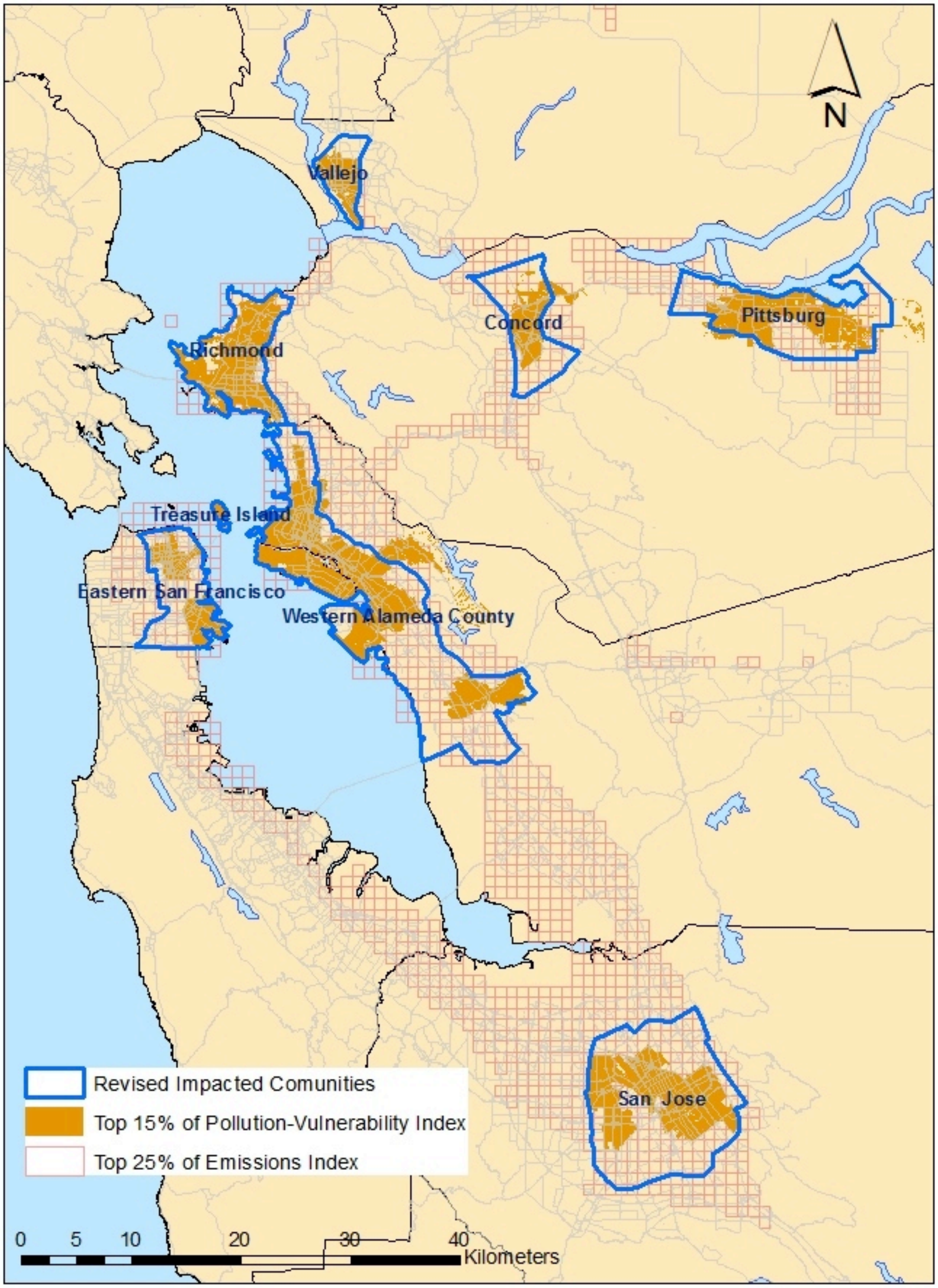

Figure 7. Revised (version 2) impacted communities (blue line) shown with the top 15% of the pollution-vulnerability index (brown) and the top 25% of the emissions index (red squares).

The version 2 map (Figure 7) includes seven impacted communities: Richmond/San Pablo; eastern San Francisco, including Treasure Island; San Jose; western Alameda County; Concord, Vallejo; and Pittsburg/Antioch.

Socioeconomic Characteristics of Zip Code Areas

Although socioeconomic factors were not used to develop the PVI, there is a strong relationship among them. $PM_{2.5}$ levels are higher for higher values of PVI (Figure 8) and life expectancy is lower for higher values of the index (Figure 9). Pollution levels and health records were inputs used to determine PVI values, so the correlations of $PM_{2.5}$ and life expectancy with PVI are as expected. However, one might not anticipate the significant tendencies for family income (Figure 10) and years of education (Figure 11) and to be lower with increased PVI since these factors were not used to in developing the PVI.

Average annual household income is more than $40,000 greater in the lowest PVI areas than the highest PVI areas, as shown in Figure 10. This difference is more than half the income level of the highest PVI areas. Note that the lowest PVI areas are not the highest income areas. The highest household incomes are in the second to lowest quintile of PVI areas suggesting that the Bay Area's highest income families do not always live in the cleanest areas, which are often rural, but do live in areas that are among the cleanest.

Areas in the lowest PVI quintile are more than 70% white, while areas in the highest PVI quintile are nearly 70% non-white (Figure 12). The percentage of Hispanics in the highest index areas is double that in the lowest index areas; the percentage of blacks is more than five times higher in the highest index areas than the lowest index areas. It is worth emphasizing that income, education level, and race and ethnicity data were not used to develop the PVI. But, although socioeconomic factors were not used, there is a clear correlation between socioeconomic disadvantage and racial minorities and the impacted communities identified by this method.

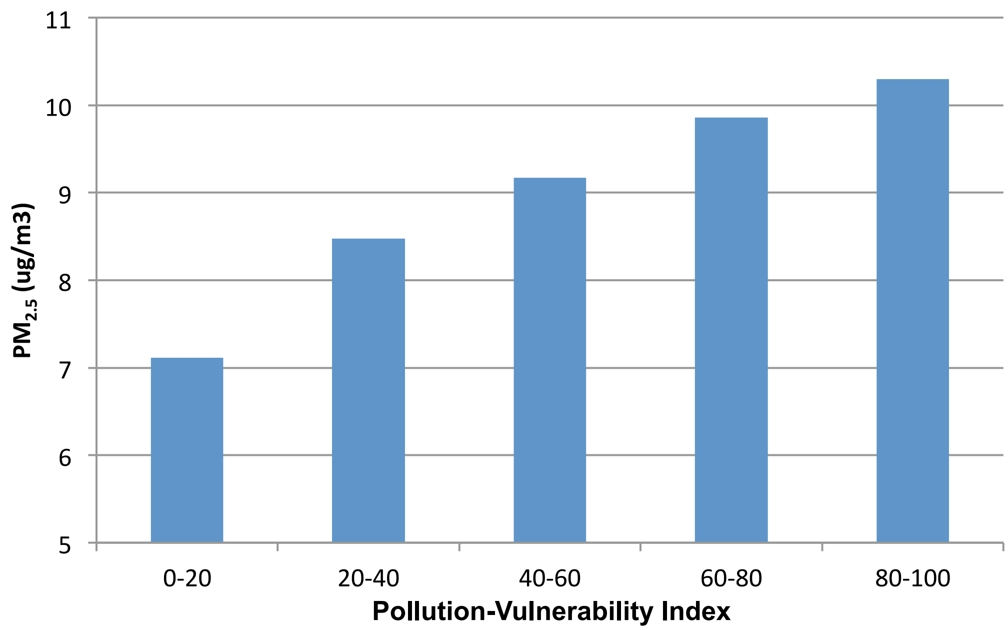

Figure 8. Mean fine particulate matter concentrations (micrograms per cubic meter) in zip code areas by pollution-vulnerability index.

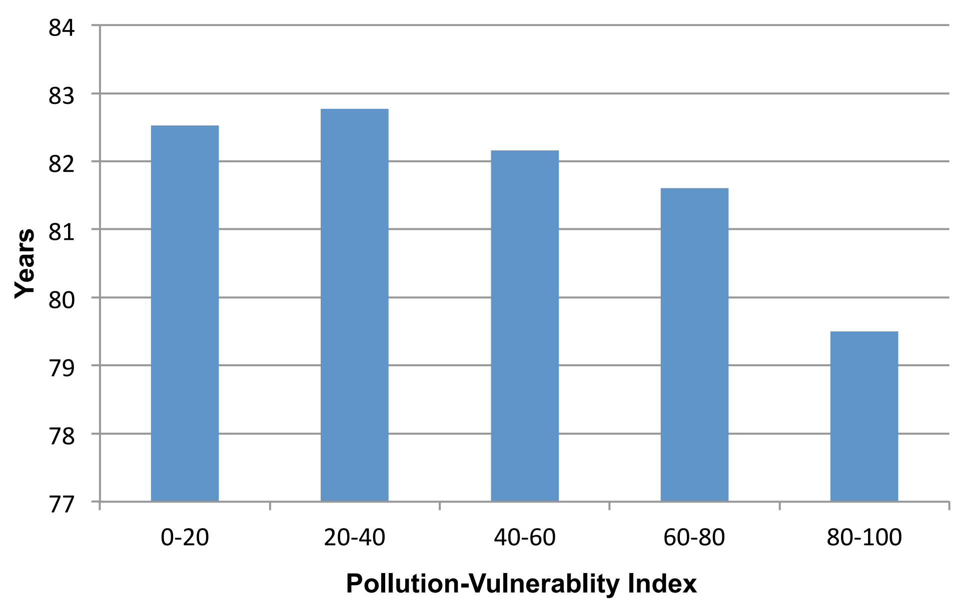

Figure 9. Mean life expectancy (years) of zip code areas by pollution-vulnerability index.

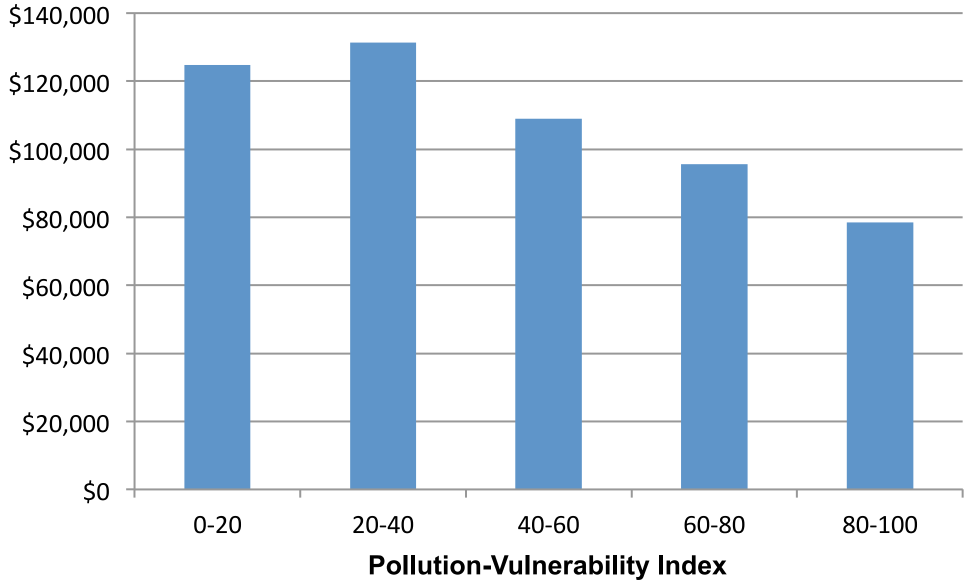

Figure 10. Mean annual household income (US dollars) of zip code areas by pollution-vulnerability index.

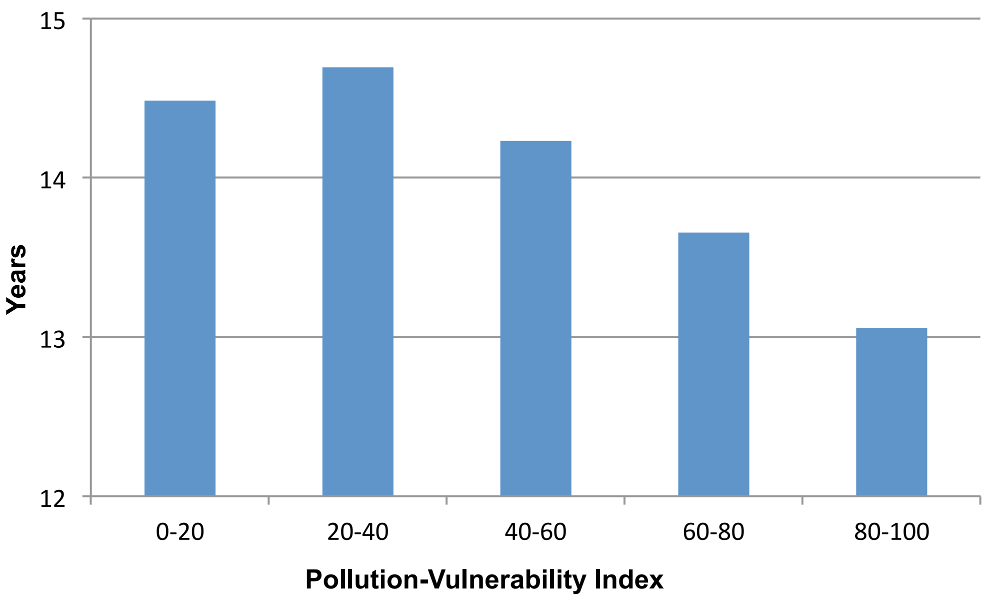

Figure 11. Mean education level (years) of zip code areas by pollution-vulnerability index.

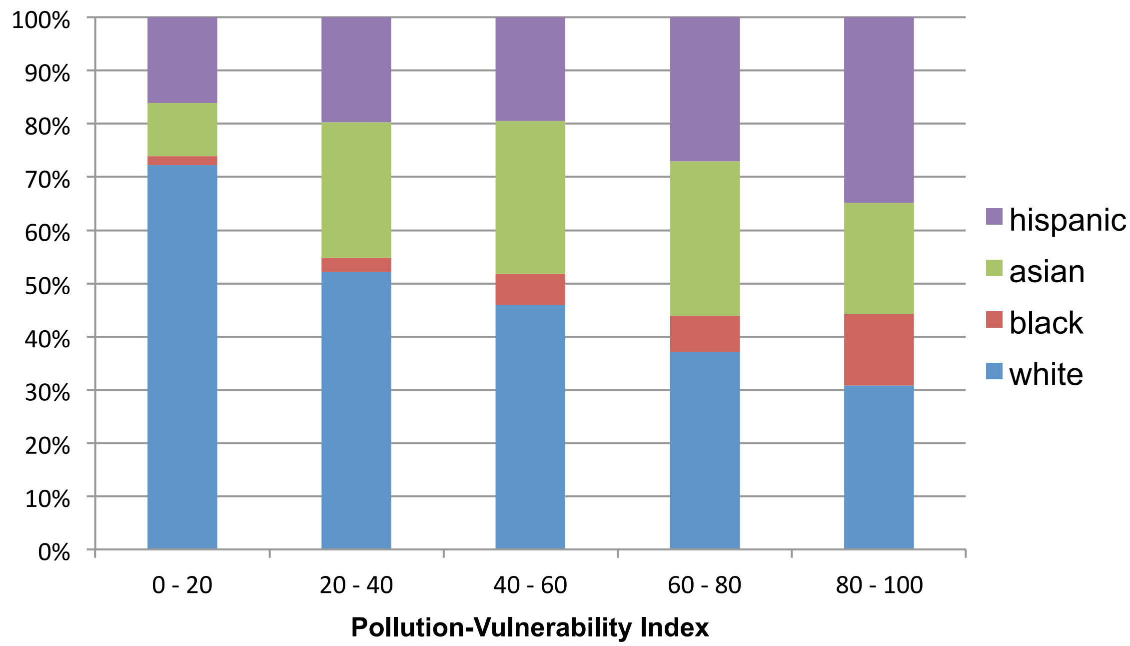

Figure 12. Race/ethnicity (percent) of zip code areas by pollution-vulnerability index.

Comparison to Other Methods

Version 2 and version 1 communities (compare Figure 13a to Figure 13b) are largely similar, but there are some important changes:

- The Redwood City/East Palo Alto area is not included in the version 2 map. This area was included in the version 1 map because of relatively high cancer risk, which is lower in the version 2 analysis due to significant reductions in emissions of diesel PM in 2015 compared to 2005. Fine PM levels in this community are generally similar to those in most other Bay Area communities and ozone values are lower.
- Two communities, Vallejo and Pittsburg/Antioch, have been added in the version 2 method.
- Several communities were expanded: the eastern San Francisco area now includes Treasure Island; the San Jose area was expanded to the west; the western Alameda County area was expanded to the bay coast and now includes the City of Alameda, where pollution levels are relatively high; and the Concord area was expanded to the north.

The fact that two communities were added and several were expanded by the updated method does not imply that pollution in the Bay Area is getting worse. In fact, air pollution levels have been dropping in nearly all Bay Area communities. The addition and expansion of areas is due to the fact that new pollutants, primarily $PM_{2.5}$, were added to the version 2 methodology. Adding $PM_{2.5}$ has expanded communities relative to the version 1 method that only considered carcinogenic toxic air contaminants.

Although they used different approaches, the Air District's version 2 methodology (Figure 13b) and the Environmental Justice Screening Method (EJSM, Figure 14) and CalEnviroScreen (Figure 15) identified similar areas. The Air District's version 2 method identified areas directly impacted by air pollution using cancer risk for toxic compounds and the BenMAP method for $PM_{2.5}$ and ozone, considering the influence of underlying health on $PM_{2.5}$ and ozone impacts. CalEnviroScreen and EJSM used pollution levels, proximity to sources, socioeconomic and demographic factors, and health records. In spite of these differences, the similarity of outcomes between the methods is evident.

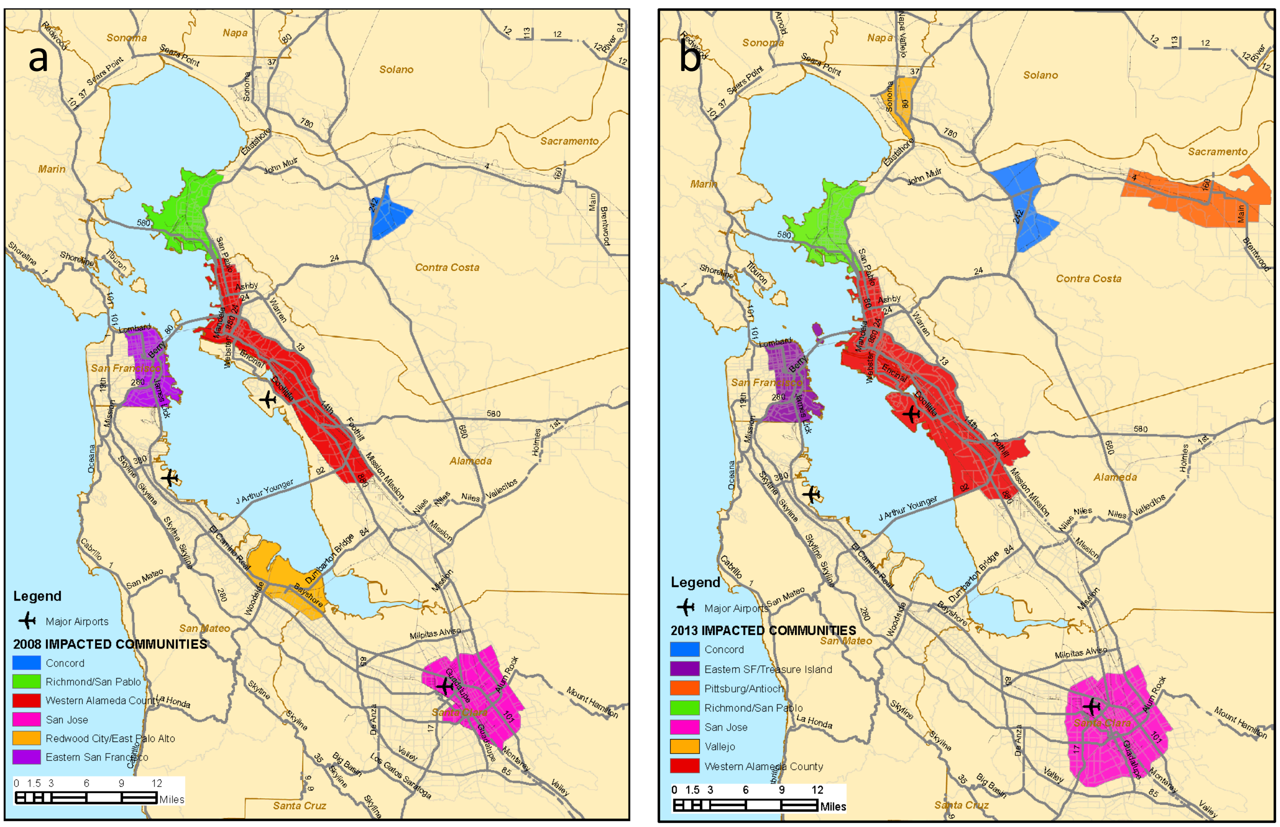

Figure 13. Impacted areas identified by (a) the initial version 1 method and (b) the updated version 2 method.

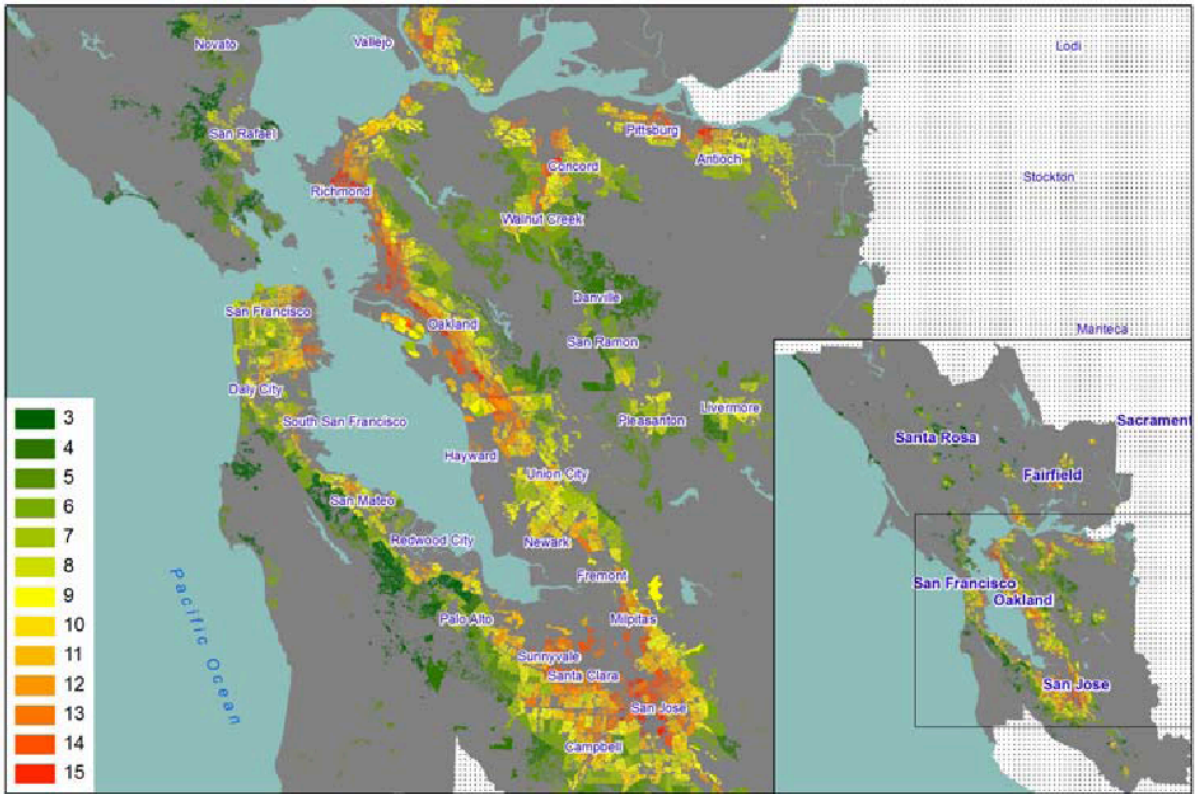

Figure 14. Environmental Justice Screening Method (color shaded areas) with values of the method's combined screening index indicated.

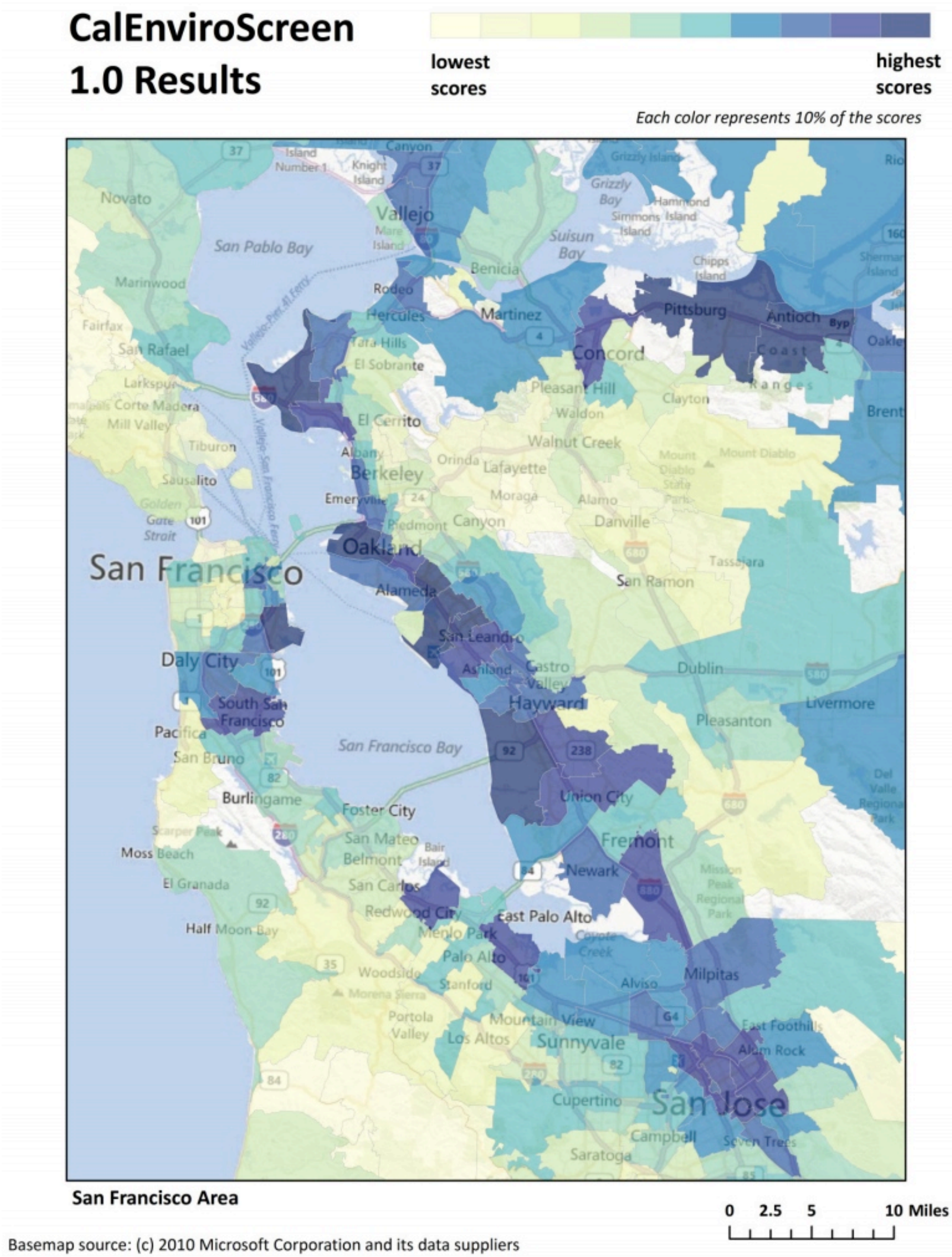

Figure 15. CalEnviroScreen Version 1 (color shaded areas) with values of the method's combined screening score indicated.

Comparison Indices

To understand the factors contributing to the highest impact areas, two additional indices were created and compared to the PVI (Figure 16a). The effects of air pollution levels only, without the influence of local health outcome records, can be seen in the pollution index (PI, Figure 16b), which uses a single average set of mortality and morbidity base rates for the entire Bay Area. The effects of local health records, without the air pollution information, are shown by the vulnerability index (VI, Figure 16c), which is highest where recorded health outcomes are worst. It is important to note that values of VI are determined mostly by factors other than air pollution. For example, analysis for this study found that outdoor air pollution contributes less than five percent of the non-accident mortality rate. While this is significant, other factors related to other environmental pollutants and to economic and social disadvantage in a broad sense appear to play a larger role in differences in health outcomes among communities.[23]

The PVI accounts for population vulnerability but tends to be high where air pollution is relatively high. Generally areas with high PVI values also have high PI values: the two indices identify approximately the same areas. However, the health data in the PVI does modify the extent of areas. For example, the PVI has higher values for areas in southwestern Alameda County and for areas near and west of Antioch, and lower values in much of San Jose.

Areas with high PI often overlap areas with high VI. For example, parts of western Alameda County, Richmond, and Concord and Vallejo have high values of both indices. However, PI values are higher than VI values in many parts of San Francisco, Alameda, and San Jose, areas where air pollution is predicted and observed to be high. VI values are generally higher for northern portions of the Bay Area—Antioch, Fairfield, and Santa Rosa—in comparison to PI values, and generally lower in the south. For example, in Fairfield VI is high but PI is relatively low. In San Jose, PI is high for many zip code areas, but VI is relatively low in most areas.

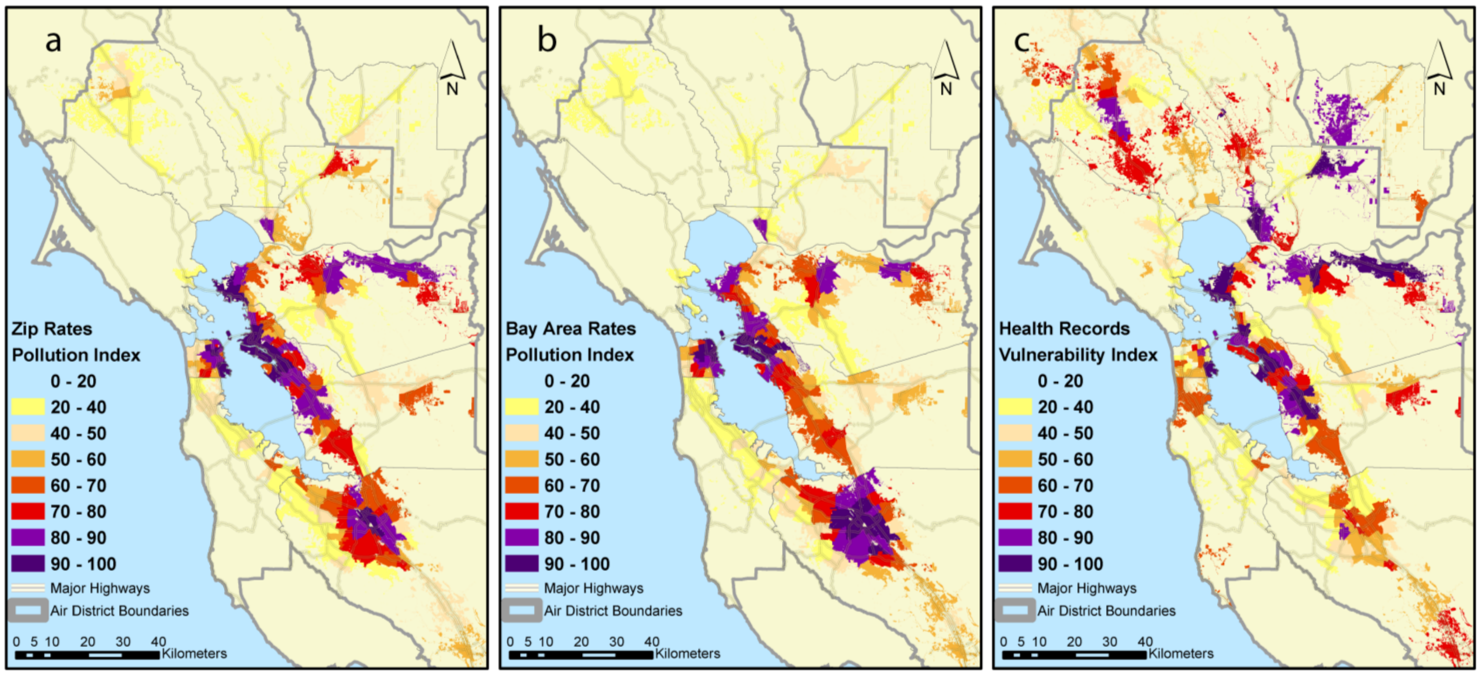

Figure 16. (a) The pollution vulnerability index compared to (b) the pollution index and (c) the vulnerability index.

DISCUSSION AND NEXT STEPS

The Air District has developed an updated method for identifying impacted communities. The updated method maps air pollution's health impacts in the Bay Area. It uses detailed, current information on air pollution concentrations in determining the health impacts. It also considers population vulnerabilities, by incorporating Bay Area health records, in determining air pollution health impacts.

Purpose of the Maps

The version 2 maps of impacted areas incorporate new data and methods. However, the fundamental purpose of the maps remains the same: to identify and map areas within the Bay Area with relatively high levels of air pollution and with residents who are relatively more vulnerable to the harmful health impacts of air pollution. The Air District's specific objectives in updating maps of impacted areas were to:

- Identify vulnerable populations by directly estimating health impacts of air pollution;
- Consider additional pollutants. Specifically, identify areas with highest heath impacts from exposure to fine PM and ozone, in addition to cancer risk from TAC;
- Consider existing rates of air-pollution related diseases in estimating heath impacts; and
- Develop maps to prioritize and focus activities that mitigate air pollution exposures and direct special studies, as before.

These regional maps will be used to help prioritize and focus the Air District's activities and resources. For example, in impacted areas the Air District will continue to

- Prioritize grant funding for projects that reduce emissions;
- Focus enforcement activities;
- Develop new and revised regulations that consider source categories contributing to local impacts;
- Develop local planning guidance and highlight plans and programs to reduce exposures in these communities;
- Focus outreach and community education and engagement programs; and
- Conduct special studies to measure and model local air pollution impacts.

More discussion on the uses for maps of impacted communities is provided in a CARE program summary report.[1]

Strengths of the Method

The version 2 methodology considers multiple air pollution impacts: cancer risk from toxic air contaminants (TAC) and mortality and morbidity from $PM_{2.5}$ and ozone. Using a BenMAP approach, it considers vulnerability to air pollution by incorporating local rates of existing health impact. An examination of population demographics—including income, education, and race/ethnicity—within impacted zip code areas reveals a clear connection between socioeconomic disadvantage and impacted areas. Because the method provides a link between air pollution and health impacts, we can target areas with the greatest impacts and target sources that contribute to those impacts.

Compared with other methods, an advantage of the version 2 method is that it starts to establish quantitative links, based on scientific studies, between parameters included and the final metric by which communities are compared. Specifically, in identifying impacted areas, the method relies primarily on the pollution-vulnerability index produced using assessment methods developed by state and federal researchers to quantitatively link air pollution levels to health outcomes. In so doing, it provides a direct link between the factors included in the method and health outcomes in the impacted areas. A critique of EJSM and CalEnviroScreen methods is that the many parameters they include as scoring criteria are given equal weights because their relative importance to health outcomes are unknown. For example, an indicator of $PM_{2.5}$ concentrations is weighted equally with an indicator of educational attainment.

As quantitative options for defining impacted communities become available, adopting them seems a sensible goal as we seek to provide a method for prioritizing resources and seek to determine the relative importance of factors creating health impacts.

Caveats and Considerations

It should be noted that the version 2 method only considers air pollution levels and *quantifiable and attributable* health effects. In contrast, the EJSM and CalEnviroScreen methods focus on a multimedia approach by including environmental conditions and population characteristics that include health status and socioeconomic factors as modifying components of *potential* impact.

For all methods of identifying impacted areas, the methods are only as good as the inputs supporting them. In this updated methodology, providing high quality inputs of $PM_{2.5}$ and TAC concentrations, with high spatial detail, is critical. Modeling uncertainties and lack of spatial detail in creating these inputs will clearly have a negative effect on the method. Although measurements were used to enhance the modeling estimates, the measurement networks for $PM_{2.5}$ and TAC are relatively sparse for this application, and may not provide adequate assurance of precise inputs. Mobile sampling, for example using the Air District's mobile sampling van, could help fill important gaps in our understanding of local air pollutant concentrations.

Providing high quality health records, also with a high degree of spatial detail, is equally important. Zip code level health data and analyses may be too coarse in some areas; this is an important consideration when zip code areas are large and span a wide range of pollution levels and population demographics.

Hospitalizations and emergency room records were the best data available at the time of this study. Ideally, however, it would be preferable to have measures of prevalence for asthma and other conditions to identify population vulnerabilities.[24] Using hospitalizations and emergency room visits does highlight communities that have poor access to care. More affluent communities tend to have better preventative care so when residents have asthma attacks they are more likely to avoid emergency room visits and instead use medication. However, data on numbers of people suffering from asthma in all Bay Area communities would be a useful addition to the method.

The decision to apply age adjustments was reached after much consideration and experimentation. No age adjustment gives more weight to zip code areas with relatively more children or seniors than the Bay Area average. Initially this was seen as a preferred approach, since the version 1 method specifically included youth and senior populations. However, in practice our finding was that areas identified were similar with and without age adjustment, except that without age adjustment retirement communities were highlighted. These were areas where pollution levels were relatively low, life expectancies were higher than the Bay Area average, and the population was generally healthy, but where mortality rates were high because the average age of the population was relatively high. In light of these findings, the decision was made to apply age adjustments, as described in Appendix C.

A shortcoming this method and others share is the inability to clearly and precisely identify specific emissions source areas that contribute to air pollution and health impacts in the impacted areas.

Once we identify areas of impact, the question arises where should we reduce emissions, and what type of emitted pollutants, to produce the greatest benefit? Focusing on emissions within and adjacent to areas of impact is a reasonable first step, but ideally one would have a more precise tool for addressing this question.

The updated maps, like the initial maps of impacted areas, provide a "macro-scale" identification of impacted communities. This means that communities identified in the maps share characteristics that suggest greater health impacts from air pollutants relative to other areas in the region. While a macro-scale analysis is sufficient and appropriate for focusing Air District resources, it is not useful for project-level planning, where a more local-scale analysis is required. At the level of individual neighborhoods, blocks, and streets this macro-scale analysis will likely miss impacts and local variability that are important at a local scale. Even outside impacted communities there may be busy roads or local emissions sources that create air pollution health impacts. Conversely, not all neighborhoods in the impacted communities necessarily face greater health threats. There is a greater density of relatively unhealthy neighborhoods in the impacted communities; but, there are also neighborhoods within impacted communities that are just as healthy as other parts of the Bay Area. This is to say, additional analysis is required to estimate health impacts at a specific location, whether it be within or outside an impacted area.

Future Work

In the near-term, the next two to three years, the Air District will focus on developing and collecting datasets to further improve the spatial detail of both input concentrations and input health records used in the identification of impacted areas. A higher level of detail in these key inputs will help identify neighborhoods and communities that may be missed in the current macro-scale analysis. Specifically, the Air District will investigate the following:

1) Improve the accuracy and spatial detail of estimated air pollution concentrations, especially of $PM_{2.5}$ and TAC. This may be achieved by higher resolution air pollution modeling in the case of $PM_{2.5}$, but may also rely on mobile sampling and on high-density supplemental monitoring in some areas;

2) Use near-roadway dispersion modeling results already developed by the Air District for State highways to represent local-scale health impacts from freeways and busy roadways; and

3) Work with county and State health departments to obtain the spatial detail of health outcome data. The Air District staff is currently working with local health departments and other researchers to obtain and analyze address-level mortality data.

In the longer term, the Air District will work to expand the types of factors include in the Air District's identification of impacted areas and pursue methods of linking health impacts to source emissions areas. The Air District will investigate the following:

1) Explore improved measures of prevalence and incidence of health outcomes, beyond emergency room visits and hospital admissions. In some communities, incidents of asthma and other conditions may be high but preventative care keeps residents out of emergency rooms;

2) Consider health impacts related to climate change. In November 2013, the Air District's Board of Directors adopted a resolution setting a regional goal of reducing greenhouse gas emissions and calling for a Work Program that outlines steps the Air District will take toward the goal. One of the elements of the Work Program is a "Climate Change and Public Health Impacts Initiative," which would identify strategies to assist the Bay Area's most vulnerable populations and impacted communities and begins to integrate the Air District's climate protection program with the CARE program. Considering health impacts related to climate change could lead to additional changes in the method to identify impacted areas; and

3) Develop methods to identify the emissions source areas and pollutants that contribute most to the impacted communities. The Air District staff is currently working with the University of California at Berkeley researchers to develop an adjoint modeling approach[25] to address this issue.

These considerations will help to continue to define areas in which to focus mitigations through Air District programs and initiatives and to track progress in reducing air pollution exposures and health effects.

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