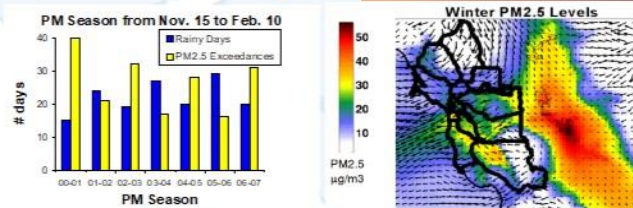


Air Toxics Data Analysis and Regional Modeling In the San Francisco Bay Area to Support AB617

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1. Introduction

1.1 Background

The adoption of Assembly Bill 617 (AB617) established collaborative programs to reduce community exposure to air pollutants in neighborhoods most impacted by air pollution. Air District staff have been working closely with the California Air Resources Board (ARB), other local air districts, community groups, community members, environmental organizations, regulated industries, and other key stakeholders to reduce harmful air pollutants in Bay Area communities.

One purpose of this data analysis and regional modeling effort is to support the District's AB617 activities by assessing pollutant formation, quantifying the relative contribution of emission sources to ambient pollution levels, and assessing population exposures and the benefits of emission controls in impacted communities around the Bay Area. Another purpose is to support the AB617 activities by identifying geographic areas that are significantly overburdened relative to the Bay Area as a whole, prioritizing among the overburdened areas for AB617 community selection and characterizing relative ambient concentrations in rural, suburban and urban areas. Results of this effort are expected to help identify strategies for reducing regional concentrations of key species of air toxics. Analyses in this report focus on air toxics concentrations in the whole Bay Area with an emphasis on West Oakland. Follow-up analyses will include other Bay Area communities.

For the air toxics analyses, we evaluated ambient meteorological and air quality data, and applied the U.S. EPA's Community Multi-Scale Air Quality (CMAQ) model to simulate pollutant concentrations at a 1-km horizontal resolution over the entire Bay Area for 2016 (Figure 1.1). Then we repeated the simulation with West Oakland's anthropogenic emissions removed from the modeling inventory, leaving all other model input parameters unchanged. We calculated annual average air toxics concentrations using the output of each simulation. The first simulation provided the annual average air toxics concentrations for 2016 over the entire Bay Area, which will be used for air toxics cancer risk evaluation. The second simulation provided an estimate of background air toxics levels in West Oakland (i.e., the air toxics concentrations that would exist in the absence of local West Oakland sources).

Background air toxics concentrations will be combined with local-scale modeling of West Oakland sources using the AERMOD dispersion model to provide a complete picture of air toxics levels in the community and the relative contribution of different emission sources to those levels. Figure 1.2 shows the AERMOD modeling domain for West Oakland. The area outlined in blue represents the "source domain," and all significant emissions sources in that

area will be modeled in the AERMOD simulations. The red hatched area represents the “receptor domain,” or the area for which pollutant concentrations will be calculated by AERMOD.

The application of the CMAQ model involves the preparation of meteorological and emissions inputs, model runs, analysis of simulated pollutant concentrations, and the evaluation of model performance via comparison between simulated and observed pollutant concentrations. A simulation year of 2016 was selected because (1) this is a recent year that is likely to be representative of current conditions in West Oakland and other communities; and (2) special measurement studies that took place in 2016 provide additional ambient data to support evaluations of model performance.

A total of 11 air toxics were simulated: diesel particulate matter (DPM), 5 toxic gases (acetaldehyde, acrolein, benzene, 1,3-butadiene, and formaldehyde), and 5 trace metals (cadmium, chromium VI, lead, mercury, and nickel). Previous analyses have indicated that DPM and the 5 toxic gases cumulatively account for more than 90% of toxic air contaminant emissions in the Bay Area (Tanrikulu et al., 2011).

District staff have been applying and evaluating the CMAQ model in the Bay Area over the last several years, along with the Weather Research and Forecasting (WRF) model, which provides meteorological inputs for CMAQ. Findings from previous modeling work are documented in District reports on air toxics data analysis and modeling (Tanrikulu et al., 2009 and 2011) and PM_{2.5} data analysis and modeling (Tanrikulu et al., 2019), as well as in the District’s 2017 Clean Air Plan (BAAQMD, 2017). Both the CMAQ and WRF models were tested and evaluated for many cases in the Bay Area, and their performance has been iteratively improved. The 2016 simulations used the best-performing configuration of the model. The 2016 emissions inputs have been updated to reflect ARB’s most recent estimates and have been evaluated to the extent possible.

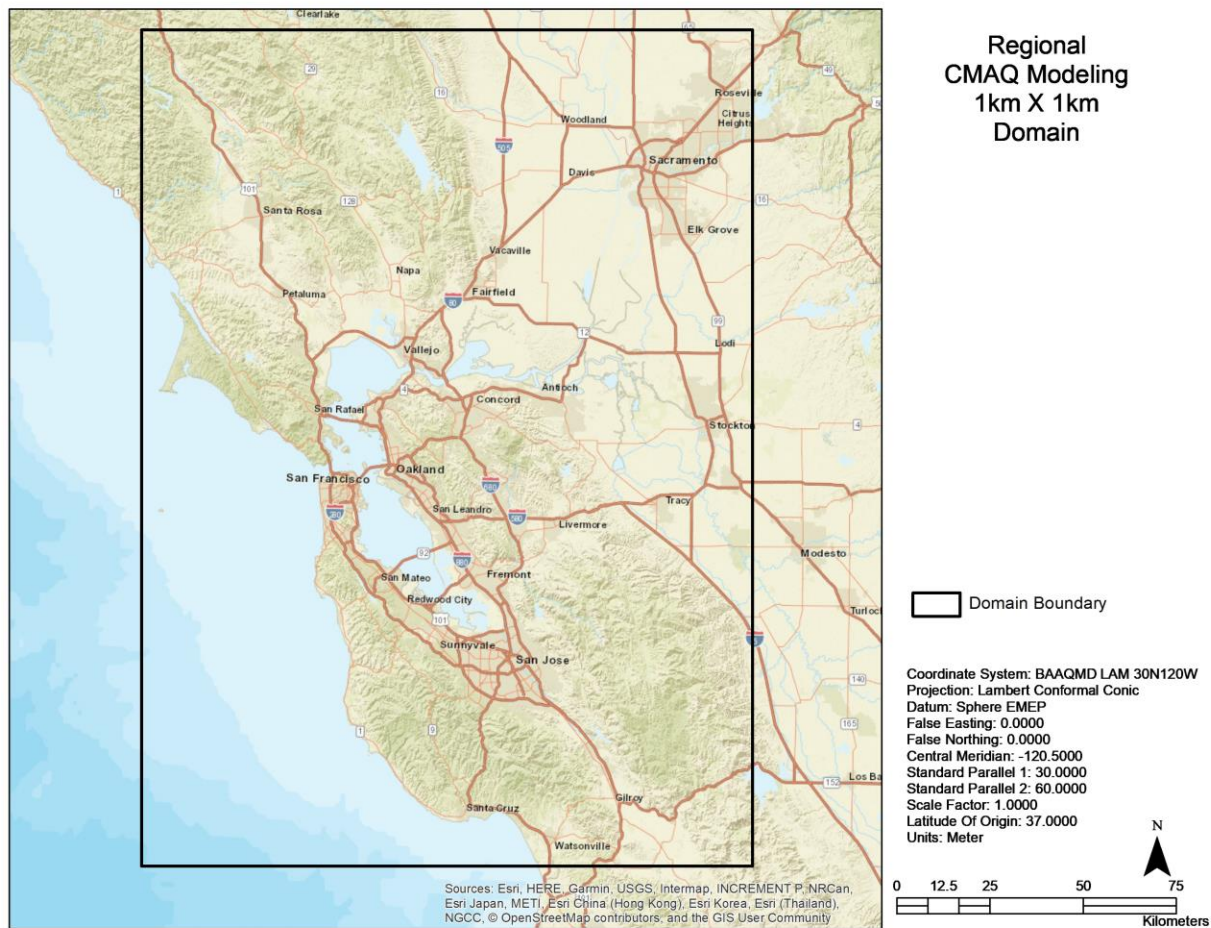


Figure 1.1: The regional 1-km modeling domain used for CMAQ simulations.

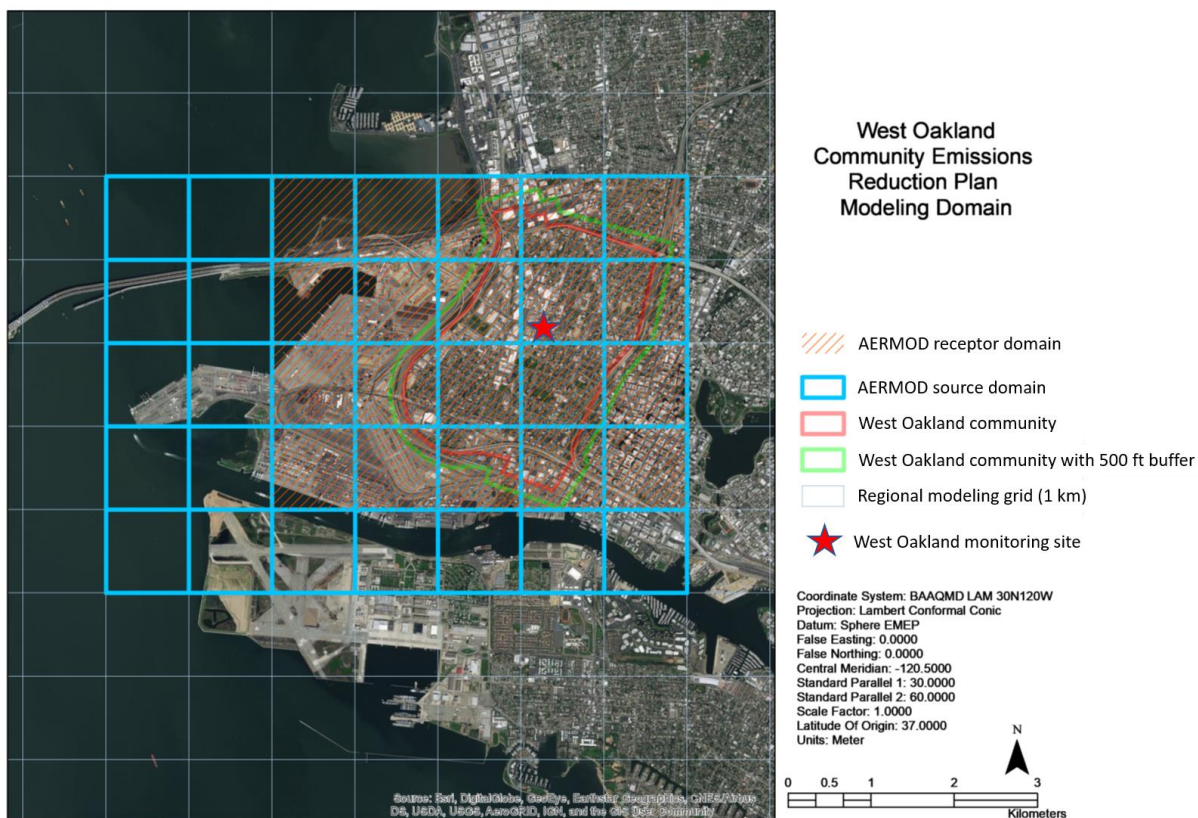


Figure 1.2: The West Oakland AERMOD modeling domain. The area outlined in blue represents the AERMOD source domain, and the red hatched area represents the AERMOD receptor domain.

1.2 Air Toxics and Their Health Impacts

Air toxics are a complex mixture of gases, suspended particles and liquid droplets in the atmosphere. Most air toxics originate from human-made sources, including mobile sources (e.g., cars, trucks, buses) and stationary sources (e.g., factories, refineries, power plants), as well as indoor sources (e.g., some building materials and cleaning solvents). Some air toxics are also released from natural sources such as forest fires.

One of the major human health outcomes resulting from air toxics exposure is cancer risk. The unit risk factor describes the excess cancer risk associated with an inhalation exposure to a concentration of $1 \mu\text{g}/\text{m}^3$ of a given toxic air contaminant (assuming a 70-year lifetime exposure). Table 1.1 lists unit risk factors for the modeled air toxics that were recently updated based on CAPCOA recommendations. Unit risk factors for toxic metals tend to be higher than those of other air toxics; for example, the unit risk factor for hexavalent chromium is orders-of-magnitude higher than unit risk factors for other air toxics. However, typical atmospheric concentrations of toxic metals are much smaller than those of other toxics; thus, overall cancer risks due to the metals are relatively small.

Table 1.1: Inhalation unit cancer risk factors for the air toxic species included in this study.

Air Toxics¹	Unit Risk Factor (($\mu\text{g}/\text{m}^3$)⁻¹)
Formaldehyde	0.000014
Acetaldehyde	0.0000068
Benzene	0.000068
1,3-Butadiene	0.00041
Diesel PM	0.00074
Hexavalent Chromium	0.38
Nickel	0.00062
Cadmium	0.010
Lead	0.00066

¹Acrolein and mercury were also simulated in this study; however, they have no known cancer risk. Therefore, they are not included in this table.

Section 2 of this report presents a summary of air toxics observations in the Bay Area and results of analysis of observed data; Section 3 presents modeling methods, including emissions inventory preparation, preparation of meteorological inputs and application of the CMAQ model. Section 4 presents model evaluation. Section 5 presents the excess cancer risk associated with air toxics. Section 6 presents a summary and discussion of overall results.

There are several appendices that provide additional details on air toxics emissions estimates (Appendix A), primary vs. secondary air toxics formation (Appendix B), simulation of toxics metals (Appendix C), and West Oakland-specific cancer risk evaluation (Appendix D).

Simulation of toxics metals is discussed in Appendix C rather than the main body of this report because the emissions estimates for these species are preliminary and uncertain. In the absence of local data, emission estimates for metals were taken from the EPA's 2014 National Air Toxics Assessment (NATA) inventory and may be unrepresentative of 2016 emission levels in Bay Area communities. Simulated metal concentrations presented in Appendix C are preliminary and will be updated when improved emissions estimates are available. Note that, while these preliminary contributions of metals to Bay Area total cancer risk are included in the overall results, at their currently estimated levels, metals contribute only about 2% to the total Bay Area cancer risk.

2. Observations and Data Analysis

2.1 Ambient Measurements

Ambient air toxics data have been continuously collected in the Bay Area for many years. In 2016, there were 20 air toxics monitoring stations operating in the Bay Area. These stations, which are listed in Table 2.1 along with their sampling schedules, can be categorized into two types: (1) National Air Toxics Trend Stations (NATTS); and (2) Hazardous Air Pollutants Stations (HAPS). There is one NATTS station (San Jose – Jackson Street) and nineteen HAPS stations (all others) in the Bay Area.

Four air toxics species (formaldehyde, acetaldehyde, 1,3-butadiene and benzene) were measured at the San Jose NATTS every 6 days in 2016. Two air toxics species (1,3-butadiene and benzene) were measured at HAPS every 12 days. Chromium, cadmium, nickel, lead, and mercury were sampled as part of PM_{2.5} speciation at Livermore, Oakland West and Vallejo every 6 days and at San Jose – Jackson Street every 3 days.

Acrolein was not measured in the Bay Area in 2016. The air quality monitoring network plan published by BAAQMD (Knoderer et al., 2017) provides additional details on the District’s monitoring network.

All ambient data used in this study were subjected to quality assurance checks and validated prior to being used. These data were used for the establishment of relationships among emissions, meteorology and air quality, and the evaluation of models. Daily average data are used for most analyses and model evaluation, but annual averages are presented here for brevity.

Table 2.1: A list of air toxics monitoring stations in the Bay Area with their sampling schedule for 2016. Highlighted columns and rows show measurement schedule.

Station	Formaldehyde	Acetaldehyde	Benzene	1,3-butadiene	EC	Chromium	Cadmium	Lead	Nickel	Mercury
NATTS										
San Jose -Jackson St.	1 in 6 days					1 in 3 days				
HAPS and speciated PM_{2.5}										
Livermore			1 in 12 days			1 in 6 days				
Oakland West										
Vallejo										

HAPS										
Berkeley			1 in 12 days							
Bethel Island										
Concord										
Crockett										
Fort Cronkhite										
Laney College										
Martinez										
Napa										
Oakland East										
Redwood City										
Richmond – 7 th St.										
San Francisco										
San Jose – Knox Ave.										
San Pablo										
San Rafael										
Sebastopol										

2.2 Data Analysis

Table 2.2 shows the annual average observed air toxics concentrations for 2016. Concentrations below the minimum detection limit are not included in the annual averages. Stations with no annual average concentration value for a given pollutant either did not have measurements for that pollutant in 2016 or did not capture any samples above the minimum detection limit. Highlighted values in Table 2.2 represent averages calculated from less than 12 samples above the detection limit.

Formaldehyde and acetaldehyde were measured only at San Jose – Jackson Street. The annual average concentrations of these species were 2.18 $\mu\text{g}/\text{m}^3$ and 1.39 $\mu\text{g}/\text{m}^3$, respectively. Over 70% of atmospheric formaldehyde forms as an intermediate product of the oxidation (combustion) of methane and other carbon compounds (Zemba et al, 2019). The remaining atmospheric formaldehyde is directly emitted to the atmosphere, mainly from its use in industrial processes such as oil refining and the production of resins for particle board and coatings. Acetaldehyde forms as an intermediate product of the oxidation of ethylene and ethanol.

Benzene and 1,3-butadiene were monitored at all Bay Area toxics monitoring stations. The highest annual average benzene concentration in the Bay Area (0.39 ppb) was at San Jose – Knox Avenue. At seven other air monitoring stations (Berkeley, Napa, Vallejo, Oakland West, Oakland East, Redwood City and San Jose – Jackson Street), the annual average benzene concentrations exceeded 0.2 ppb. Benzene is used as a constituent in motor fuels; as a solvent for

fats, waxes, resins, oils, inks, paints, plastics, and rubber; in the extraction of oils from seeds and nuts; and in photogravure printing.

The highest Bay Area annual average 1,3-butadiene concentration (0.1 ppb) was measured at the San Jose – Knox Avenue air monitoring station. Concentrations at Sebastopol, Vallejo, San Jose – Jackson Street, Redwood City and Oakland West were above 0.07 ppb, higher than the remaining Bay Area stations. Emission sources of 1,3-butadiene include: motor vehicle exhaust, manufacturing and processing facilities, forest fires or other combustion, and cigarette smoke. Higher levels of 1,3-butadiene may be found in highly industrialized cities or near oil refineries, chemical manufacturing plants, and plastic and rubber factories.

As mentioned, PM samples were speciated at four Bay Area air monitoring stations (San Jose – Jackson Street, Vallejo, Livermore and Oakland West), and concentrations of EC and five metals were extracted, among other species. As shown in Table 2.2, the annual average EC concentration at San Jose – Jackson Street is the lowest among the four stations. However, while samples were speciated at San Jose – Jackson Street throughout 2016 and averaged over the entire year, they were speciated only during winter, spring and fall months at the other three stations and averaged over those three seasons. Since PM concentrations are higher during winter months than summer months in the Bay Area, this mismatched averaging period led to lower annual average concentration at San Jose – Jackson Street compared to other three stations.

The annual average lead concentrations are significantly higher at Oakland West than at the other 3 stations (Livermore, San Jose – Jackson Street and Vallejo). At Oakland West, there were six samples during 2016 with concentrations around 100 ng/m³ and above; as a result, the annual average concentration at this station stands out.

Table 2.2: Annual average observed air toxics concentrations for 2016. Highlighted values represent averages calculated from less than 12 valid samples.

Site	Formaldehyde	Acetaldehyde	Benzene	1,3-Butadiene	EC	Chromium	Cadmium	Lead	Nickel	Mercury
	[$\mu\text{g}/\text{m}^3$]	[$\mu\text{g}/\text{m}^3$]	[ppb]	[ppb]	[$\mu\text{g}/\text{m}^3$]	[ng/m^3]	[ng/m^3]	[ng/m^3]	[ng/m^3]	[ng/m^3]
Berkeley			0.2108							
Bethel Island			0.1263							
Concord			0.1356							
Crockett			0.1399	0.0540						
Fort Cronkhite			0.0796							
Laney College			0.1991	0.0635						
Livermore			0.1785	0.0638	0.5981		11.6242	3.8260	2.2144	2.6552
Martinez			0.1494	0.0670						
Napa			0.2192	0.0666						
Oakland East			0.2360	0.0606						
Oakland West			0.2239	0.0779	0.5580		9.0201	56.9884	4.4872	2.2439
Redwood City			0.2210	0.0703						
Richmond - 7th St			0.1424	0.0370						
San Francisco			0.1731	0.0485						
San Jose - Jackson St.	2.1871	1.3921	0.2609	0.0741	0.3608	8.4436		17.4300	4.1820	
San Jose - Knox Av			0.3971	0.1067						
San Pablo			0.1841							
San Rafael			0.1602	0.0625						
Sebastopol			0.1583	0.0850						
Vallejo			0.2027	0.0838	0.4915		8.8598	3.1431	1.3480	2.7547

Data for EC and metals are components of speciated $\text{PM}_{2.5}$.

Data for chromium include all oxidation states.

3. Modeling

3.1 Emissions Inventory Preparation

Emissions inputs for the CMAQ model were prepared using the Sparse Matrix Operator Kernel Emissions (SMOKE) processing system, version 4.5, which converts emissions inventory data to the spatial, temporal, and chemical resolution required by the air quality model. CMAQ-ready emissions inputs for 2016 included 11 air toxics: diesel particulate matter (DPM), 5 toxic gases (acetaldehyde, acrolein, benzene, 1,3-butadiene, and formaldehyde), and 5 trace metals (cadmium, chromium VI, lead, mercury, and nickel).

The starting point for the emissions processing was the 2016 criteria pollutant inventories previously assembled for 1-km PM_{2.5} modeling (Tanrikulu et al., 2019). These 2016 data, which include estimates for area sources,¹ point sources, onroad mobile sources, nonroad mobile sources, and biogenic sources, were assembled from a variety of data sources, including the District's in-house emissions estimates, emissions data from ARB, and outputs from ARB's EMFAC2017 model. Additional details on data sources and processing steps for air toxics emissions estimates are provided below.

3.1.1 Toxic Gases

SMOKE disaggregates total organic (TOG) and PM_{2.5} emissions into a series of model species that CMAQ uses to represent atmospheric chemistry. For the 2016 PM_{2.5} modeling, speciation profiles developed for the SAPRC07 chemical mechanism were applied to TOG emissions from all sources, and profiles developed for the AERO6 aerosol module (AE6) were applied to PM_{2.5} emissions from all sources (Tanrikulu et al., 2019).

The SAPRC07 mechanism treats some toxic species explicitly, including acetaldehyde, benzene, and formaldehyde. However, other air toxics are lumped into model species that act as surrogates for multiple compounds with similar mass and reactivity. For the 2016 toxics modeling, existing SAPRC07 speciation profiles for TOG were modified to treat additional air toxics (acrolein and 1,3-butadiene) explicitly.² Once the revised speciation profiles were generated, the District used SMOKE to speciate existing 2016 TOG emissions estimates into the 5 toxic gases of interest, as well as other model species used by the SAPRC07 chemical mechanism.

3.1.2 Diesel Particulate Matter

To track DPM emissions separately from other PM emissions, speciation profiles related to diesel exhaust were edited to include DPM tracer species. For example, speciation profile

¹ Area sources are stationary sources such as dry cleaners that are too small or numerous to treat as individual point sources.

² The District contracted with Ramboll to perform this work.

91106 (for heavy duty diesel vehicle exhaust) was modified to include the DPM components shown in Table 1 below.

Table 3.1: DPM components for speciation profile 91106.

Component	Description	Weight fraction
DIESEL_PMEC	Elemental carbon	0.7712
DIESEL_PMOC	Organic carbon	0.1756
DIESEL_PMFINE	Unspeciated PM _{2.5}	0.049109
DIESEL_PMSO4	Sulfate	0.00295
DIESEL_PMNO3	Nitrate	0.001141

Running SMOKE with these revised diesel exhaust profiles produced separate DPM species that could be used to estimate DPM concentrations in CMAQ.

3.1.3 Trace Metals

The toxic metals of interest are not included in the AE6 mechanism; therefore, emission estimates for these species were taken from the EPA’s 2014 NATA inventory. The 2014 NATA data includes air toxics emissions estimates for the entire U.S. at the county (for area, nonroad, and onroad sources) or facility (for point sources) level. Emissions records for cadmium, chromium VI, lead, mercury, and nickel were extracted from the NATA data for all counties in the 1-km modeling domain, processed through SMOKE, and merged with emissions data for the remaining toxic species being modeled.

Additional details on SMOKE processing steps, including ancillary data sets (e.g., spatial surrogates) used in SMOKE, are provided in a companion report on the 2016 PM_{2.5} modeling for the Bay Area (Tanrikulu et al., 2019).

3.1.4 Emissions Summaries

This subsection provides emissions density plots and summary tables for DPM, the main driver of cancer risk in the Bay Area. Similar information for additional air toxics can be found in Appendix A. Figure 3.1 shows annual average DPM emissions for the 1-km modeling domain. Table 3.2 summarizes the annual average DPM emissions by county and source sector, as reported by the SMOKE emissions model. Within the District’s jurisdiction, annual average DPM emissions total 4.2 tons per day (tpd). Nonroad and onroad mobile sources account for 57% and 41%, respectively, of total DPM emissions in the Bay Area.

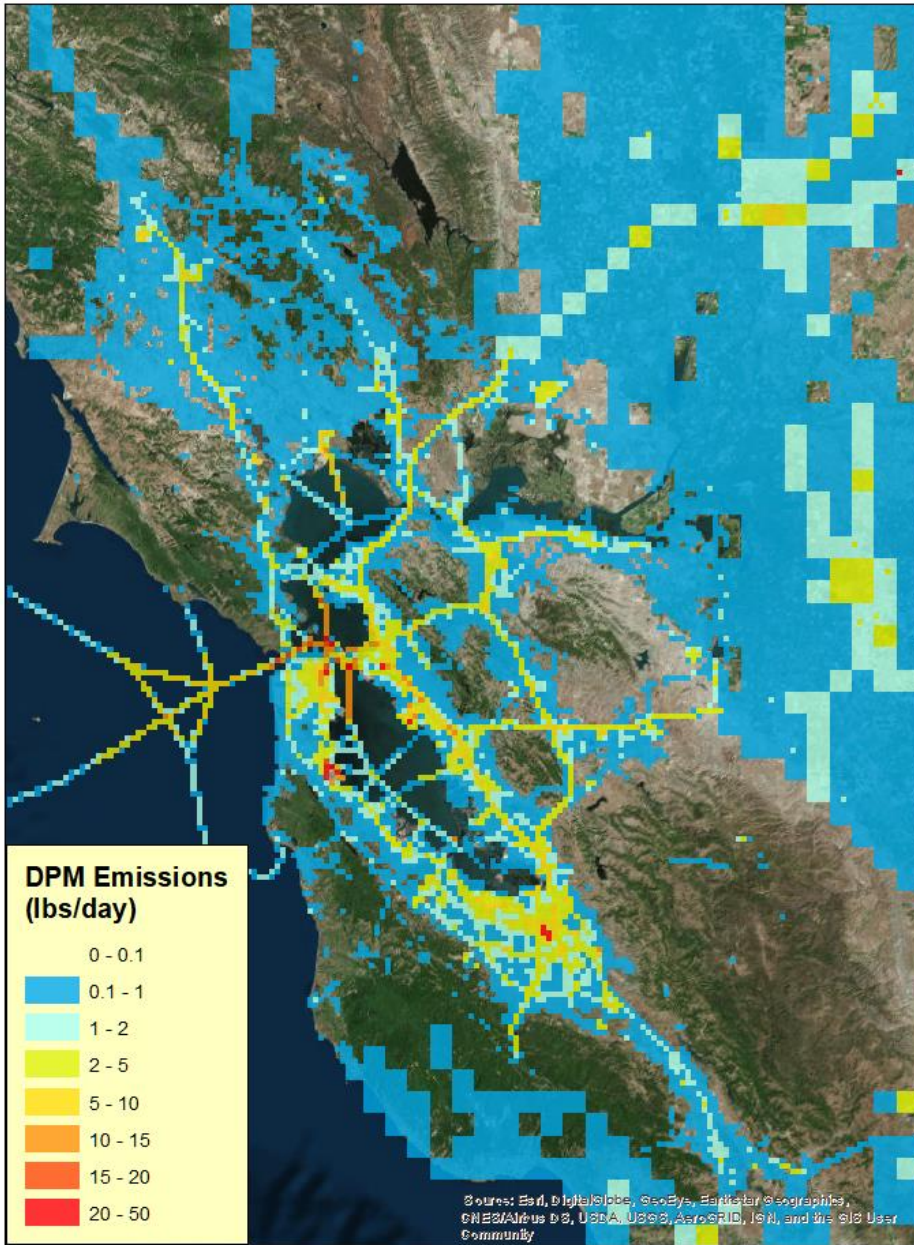


Figure 3.1: Spatial distribution of annual average DPM emissions for the 1-km modeling domain for 2016.

Table 3.2: Summary of 2016 DPM10 emissions (tpd) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.00	0.30	0.56	0.03	0.88
Contra Costa	0.00	0.23	0.23	0.00	0.47
Marin	0.00	0.09	0.05	0.00	0.14
Napa	0.00	0.10	0.06	0.00	0.16
San Francisco	0.00	0.65	0.11	0.01	0.76
San Mateo	0.00	0.38	0.10	0.01	0.49
Santa Clara	0.00	0.36	0.39	0.02	0.77

Solano ^a	0.00	0.06	0.10	0.00	0.17
Sonoma ^a	0.00	0.22	0.13	0.00	0.35
<i>BAAQMD Subtotal</i>	<i>0.00</i>	<i>2.38</i>	<i>1.74</i>	<i>0.08</i>	<i>4.19</i>
Non-BAAQMD Counties	0.02	1.44	1.11	0.03	2.60
Domain Total	0.02	3.81	2.85	0.11	6.79

^aEmissions totals for Solano and Sonoma counties only include the portion of those counties in BAAQMD's jurisdiction.

For the West Oakland AERMOD modeling domain, annual average DPM_{2.5} emissions total 0.1 tpd, or 2.4% of the BAAQMD total. Figure 3.2 shows that the distribution of emissions by source sector in West Oakland differs from the District as a whole. In West Oakland, onroad and nonroad mobile sources account for 85% of total DPM_{2.5} emissions, while the same sources account for 98% of total PM_{2.5} emissions districtwide. Figure 3.3 shows the spatial distribution of DPM emissions across the 1-km grid cells that coincide with the local-scale AERMOD modeling domain. Grid cells with high DPM emissions along the western edge of the domain are impacted by motor vehicle emissions from the Bay Bridge and marine vessel activity. Grid cells with high DPM emissions in the eastern portion of the modeling domain are impacted by motor vehicle emissions, especially from the I-880/I-980 and I-580/I-980 interchanges.

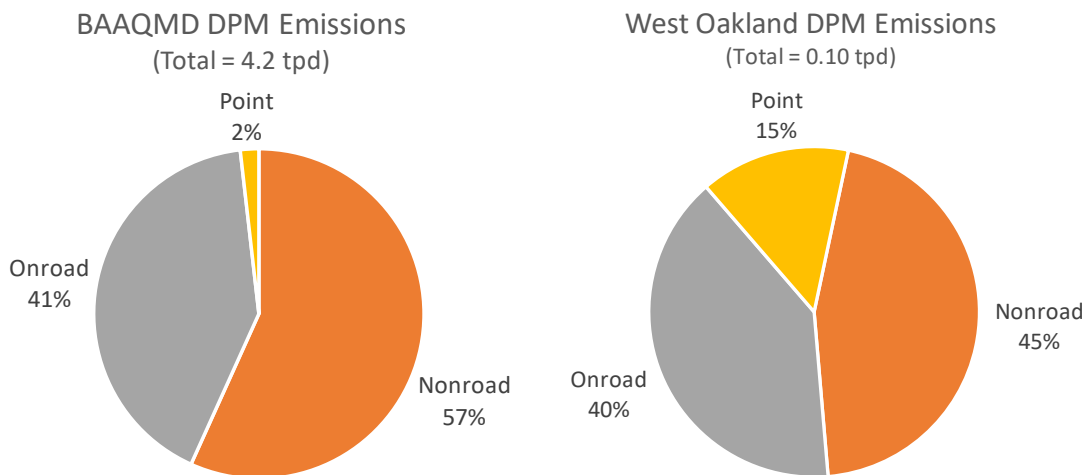


Figure 3.2: DPM emissions by source sector for the District (left) and West Oakland (right) for 2016.

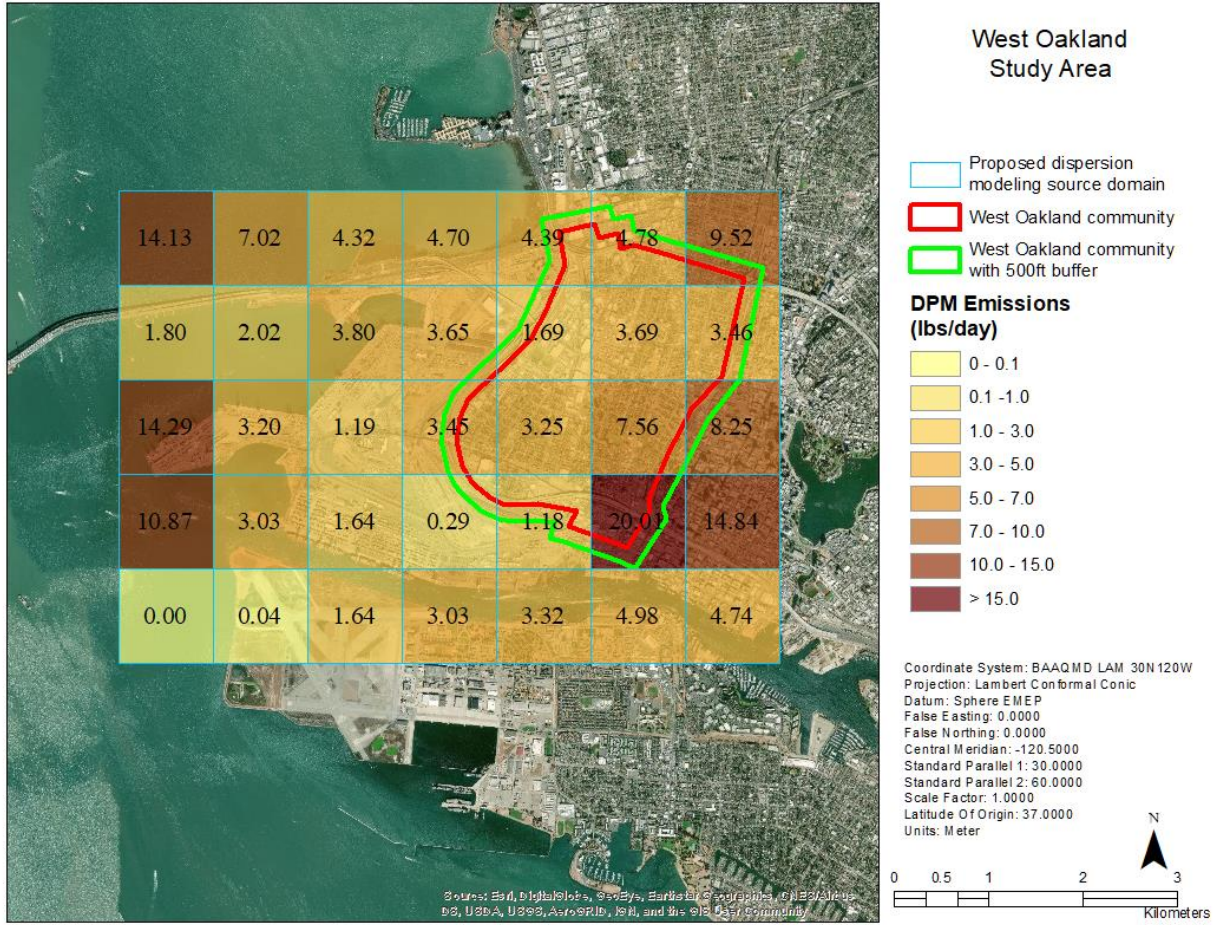


Figure 3.3: Spatial distribution of annual average DPM emissions in West Oakland for 2016.

3.2 Meteorological Modeling

The Weather Research and Forecasting (WRF) Model version 3.8 was used to prepare meteorological inputs to CMAQ. Four nested modeling domains were used (Figure 3.4). The outer domain covered the entire western United States at 36-km horizontal grid resolution to capture synoptic (large-scale) flow features and the impact of these features on local meteorology. The second domain covered California and portions of Nevada at 12-km horizontal resolution to capture mesoscale (sub-regional) flow features and their impacts on local meteorology. The third domain covered Central California at 4-km resolution to capture localized air flow features. The 4-km domain included the Bay Area, San Joaquin Valley, and Sacramento Valley, as well as portions of the Pacific Ocean and the Sierra Nevada mountains. The fourth domain covered the Bay Area and surrounding regions at 1-km resolution. All four domains employed 50 vertical layers with thickness increasing with height from the surface to the top of the modeling domain (about 18 km).

Meteorological variables are estimated at the layer midpoints in WRF. The thickness of the lowest layer to the surface was about 25 m. Thus, meteorological variables near the surface were estimated at about 12.5 m above ground level. The model configuration was tested using available physics options, including: (1) planetary boundary layer processes and time-based evaluation of mixing heights; (2) cumulus parameterization; (3) four-dimensional data assimilation (FDDA) strategy; (4) horizontal and vertical diffusion; (5) advection scheme; and (6) microphysics and radiation scheme. The final choice of options was the one that best characterized meteorology in the domain.

WRF was applied for 2016 to estimate parameters required by the air quality model, including hourly wind speed and direction, temperature, humidity, cloud cover, rain and solar radiation levels. Observations were assimilated into the model during the simulations to minimize the difference between simulations and real-world measurements. Two types of nudging methods were employed (analysis and observation). The National Centers for Environmental Prediction (NCEP) North America Mesoscale (NAM) 12-km analyzed meteorological fields were used for analysis nudging as well as for initializing the model. The NCEP ADP Global Surface and Upper Air Observational Weather Data were used for observational nudging. The analysis nudging was applied to the 36-km and 12-km domains. Frequency of surface analysis nudging was every three hours, while the frequency of 3D analysis nudging was every six hours. The 3D analysis nudging of winds was performed over all model layers, but the 3D analysis nudging of temperature and humidity was limited to layers above the planetary boundary layer. The observation nudging of wind was applied to all four domains every three hours.

The WRF model was rigorously evaluated for accuracy. Observations used to evaluate WRF were taken from the EPA's Air Quality System, the BAAQMD meteorological network, and the National Climate Data Center. Hourly and daily time series plots of observed and simulated wind, temperature and humidity were generated at each observation station and compared to each other hour by hour and day by day. Simulated hourly areal plots of wind, temperature,

humidity, planetary boundary layer height, pressure and other fields were generated and quantitatively compared against observations where observations were available.

WPS Domain Configuration

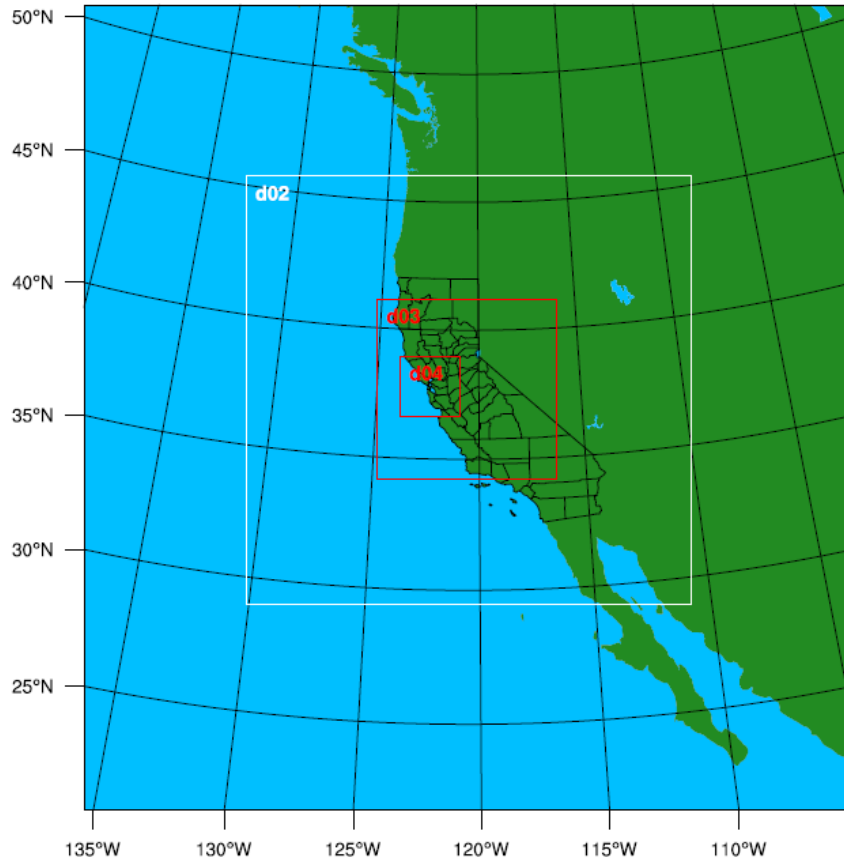


Figure 3.4: Nested WRF modeling domains.

These plots were also qualitatively evaluated for known meteorological features of the modeling domain, especially at 4-km and 1-km resolutions. These features include slope flows, channeled flows, sea breeze and low-level jet. The vertical profile of observed and simulated meteorological fields was compared at several upper air meteorological stations, including Oakland, Medford, Reno and Las Vegas, and at a temporary station established at Bodega Bay. Ramboll's METSTAT program (Emery et al., 2001) was used to statistically evaluate the performance of WRF.

The WRF model performed reasonably well in every evaluation category. The estimated bias, gross error, root mean square error (RMSE), and index of agreement (IOA) are within established criteria for acceptable model performance for every day of 2016. In other words, performance obtained from the Bay Area applications of WRF is similar or slightly better than performance obtained from applications elsewhere, available from literature. Additional information on model application and evaluation can be found in Tanrikulu et al., 2019.

3.3 Air Quality Modeling

U.S. EPA's Community Multiscale Air Quality (CMAQ) modeling system version 5.2 was used to simulate gaseous and particulate air toxics. The modeling domain is similar to that used for the District's previous air toxics modeling (Tanrikulu et al., 2009; 2011), focusing on the Bay Area at 1-km horizontal grid resolution, but extending further inland to include more surrounding regions (Figure 1.1). The vertical grid has 28 layers that extend to the lower stratosphere (~18 km) with a surface layer thickness of about 25 m. Below 1,500 m, the CMAQ layers match the WRF layers, while above 1,500 m, CMAQ layers span several meteorological model layers, which is a common practice in air quality modeling to improve computational efficiency.

The initial and boundary conditions for the 1-km modeling domain were primarily derived from the District's recent regional air quality modeling that simulated ozone and PM over the Bay Area, San Joaquin Valley and Sacramento Valley at 4-km grid resolution (Tanrikulu et al., 2019).

The standard Statewide Air Pollution Research Council Toxics Species version 2007 (SAPRC07TC) chemistry mechanism implemented in CMAQ v5.2 includes gaseous air toxics such as formaldehyde, acetaldehyde, acrolein, benzene and 1,3-butadiene (Hutzell et al., 2012). It also separately tracks direct emissions of formaldehyde, acetaldehyde and acrolein, since these compounds include a significant proportion of chemical production in the atmosphere (i.e., "secondary" production) from the oxidation of other organic compounds.

For the Bay Area application, the standard chemistry mechanism was modified to include atmospheric mercury and chemical reactions that oxidize elemental mercury to divalent mercury in both gaseous and particle-bound forms. Gaseous elemental mercury, the predominant form in the atmosphere, is relatively inert and can be transported over long distances with an atmospheric lifetime ranging from several months to a year, while both forms of oxidized mercury (often referred to as gaseous oxidized mercury and particulate bound mercury) are quickly removed from the atmosphere via wet and dry deposition, limiting their impact to a local/regional scale (AMAP/UNEP, 2013).

Formation of methylmercury by microorganisms and its bioaccumulation in the aquatic food chain are not addressed in this study. Other toxic metals added to the mechanism for the Bay Area applications include hexavalent chromium, nickel, cadmium and lead. Explicit particle emission components from diesel exhaust were also added to separately track diesel PM. The initial and boundary concentrations for the newly added species were set to a lower bound value (a negligible, but non-zero value) to avoid potential numerical problems in the model.

The CMAQ modeling was conducted for the whole year of 2016 using the complete air toxics emissions inventories described in Section 3.1 (base case) and with all anthropogenic emissions from West Oakland removed (control case). The base case represents ambient concentrations of the air toxics for 2016 over the entire Bay Area, which will be used for model evaluation and health impact assessment. The control case estimates background levels of the air toxics in

West Oakland, which will complement local-scale air dispersion model simulations to determine detailed source-receptor relationships for the area.

The simulated annual average concentrations of gaseous air toxics are discussed in section 3.3.1, diesel PM in section 3.3.2, and toxics metals in section 3.3.3.

3.3.1 Gaseous Air Toxics

Figures 3.5 through 3.9 show annual average concentrations of five gaseous air toxics (formaldehyde, acetaldehyde, acrolein, 1,3-butadiene, and benzene) from the base case CMAQ simulation over the 1-km modeling domain. The annual average concentrations are a total of primary and secondary components for species with secondary production pathways.

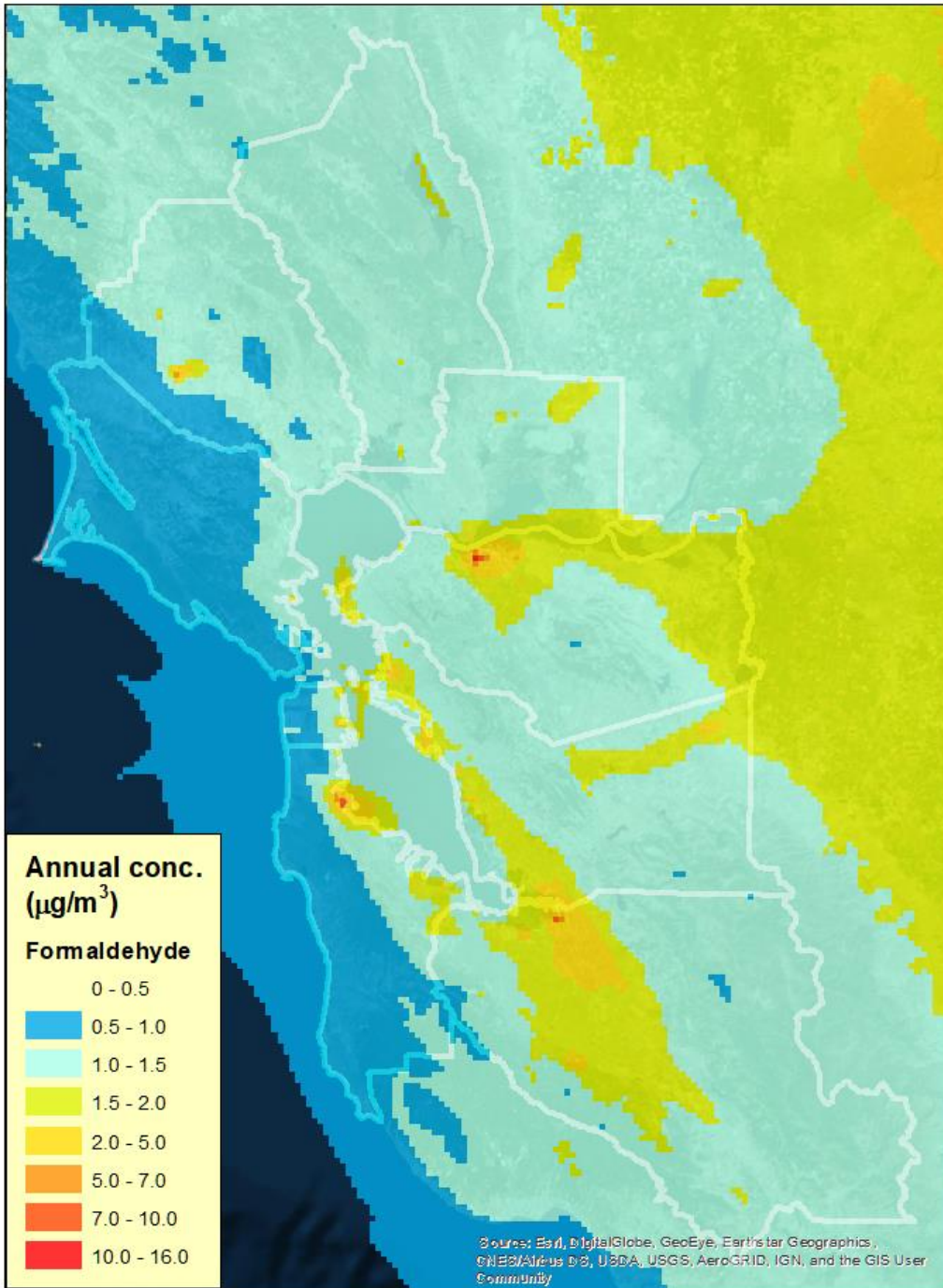
The highest annual average formaldehyde concentration is simulated at Martinez in the vicinity of the Shell Refinery, reaching $15.7 \mu\text{g}/\text{m}^3$. Other hot spots are simulated near a wastewater treatment facility in northern San Jose ($8.7 \mu\text{g}/\text{m}^3$), at San Francisco International Airport ($8.2 \mu\text{g}/\text{m}^3$), in northwestern Petaluma near a regional landfill ($6.6 \mu\text{g}/\text{m}^3$), and near Emeryville ($5.1 \mu\text{g}/\text{m}^3$). Simulated concentrations range from 2 to $5 \mu\text{g}/\text{m}^3$ in the areas surrounding these hot spots as well as at a landfill east of Livermore, and near Richmond, Oakland International Airport, Redwood City and southern San Jose. Similar concentrations are simulated along the Delta, the I-580 corridor in Livermore, and the I-880 corridor between San Leandro and San Jose.

The annual average acetaldehyde concentrations are highest at San Francisco International Airport ($2.7 \mu\text{g}/\text{m}^3$). Concentrations are also high (above $0.8 \mu\text{g}/\text{m}^3$) on the east side of the Bay Bridge, at Oakland International Airport, and in San Jose. Portions of I-80, I-880, I-680, I-101, and I-580 have elevated concentrations.

While formaldehyde and acetaldehyde in most of the modeling domain are largely due to secondary production, hot spot areas tend to exhibit relatively higher primary fractions, indicating significant contributions of local sources (see Appendix B for a discussion of primary vs. secondary toxics formation).

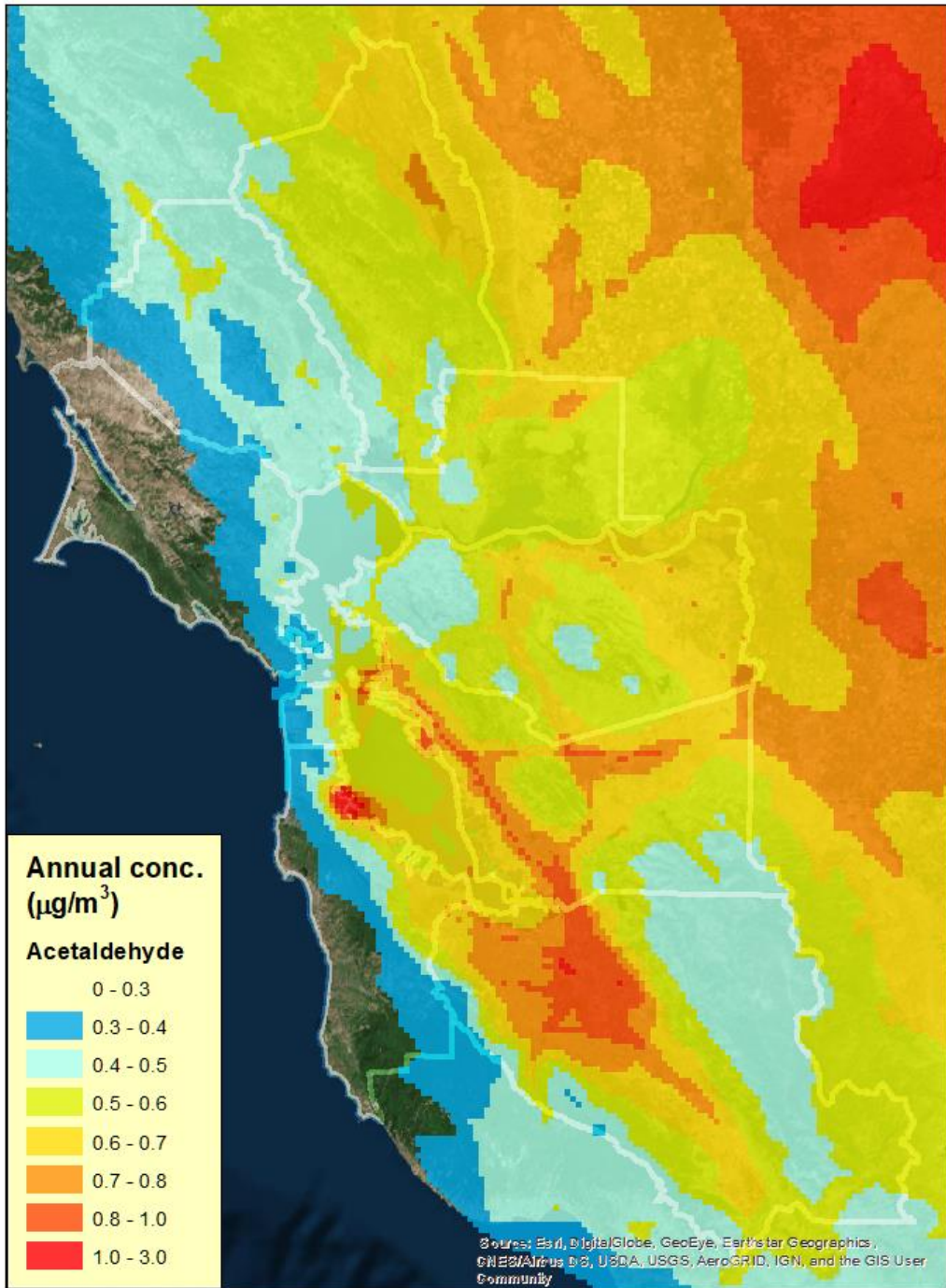
Concentration patterns of acrolein and 1,3-butadiene are similar, with both showing the highest annual average concentration at San Francisco International Airport ($1.1 \mu\text{g}/\text{m}^3$ for acrolein and $0.9 \mu\text{g}/\text{m}^3$ for 1,3-butadiene). Secondary production pathways of acrolein include atmospheric oxidation of 1,3-butadiene.

For benzene, annual average concentrations above $1 \mu\text{g}/\text{m}^3$ occur in Richmond, Martinez, northern San Jose, Mountain View, and at the San Francisco International Airport.



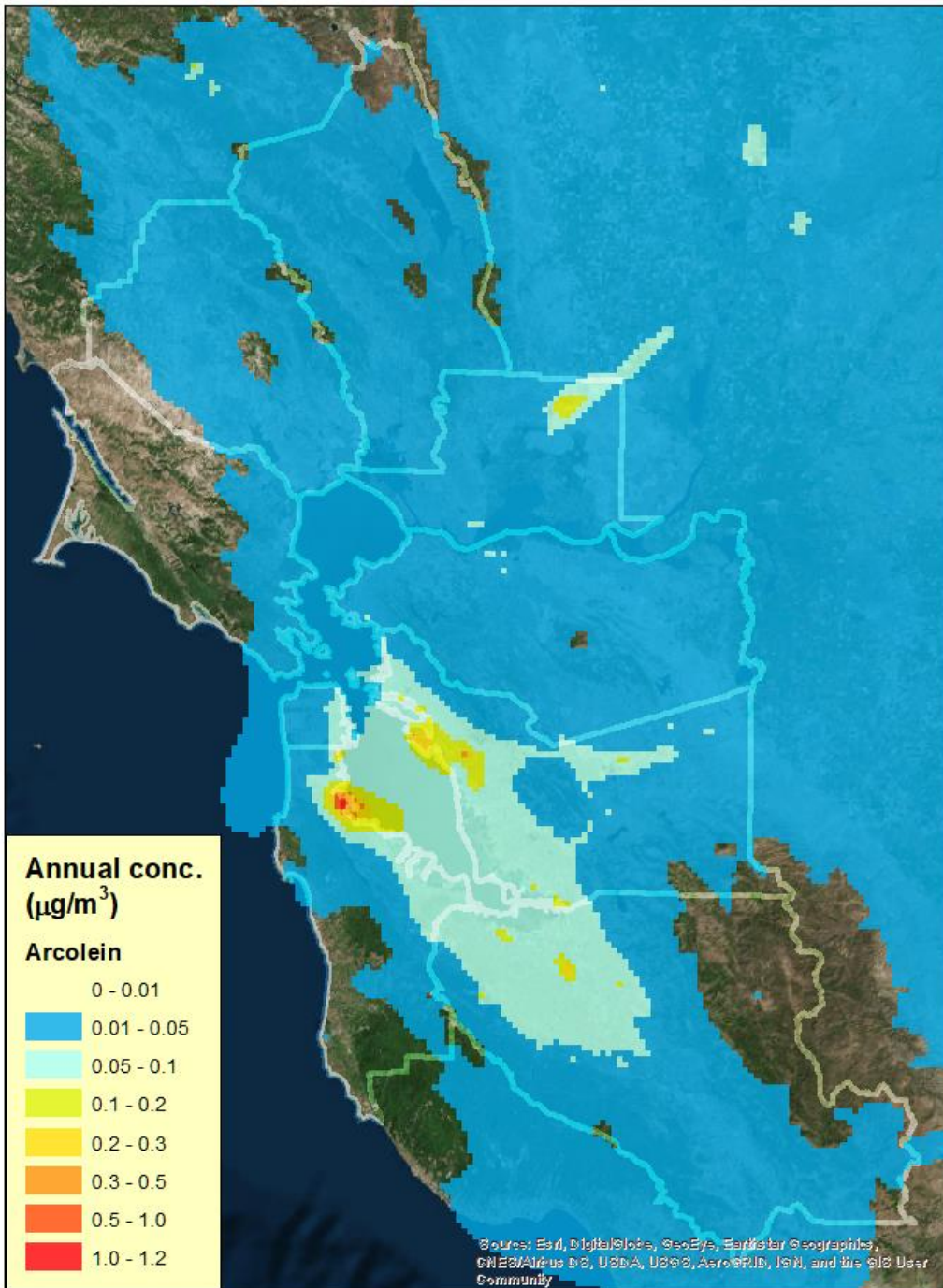
Maximum: 15.7

Figure 3.5: Annual average simulated formaldehyde concentrations for 2016.



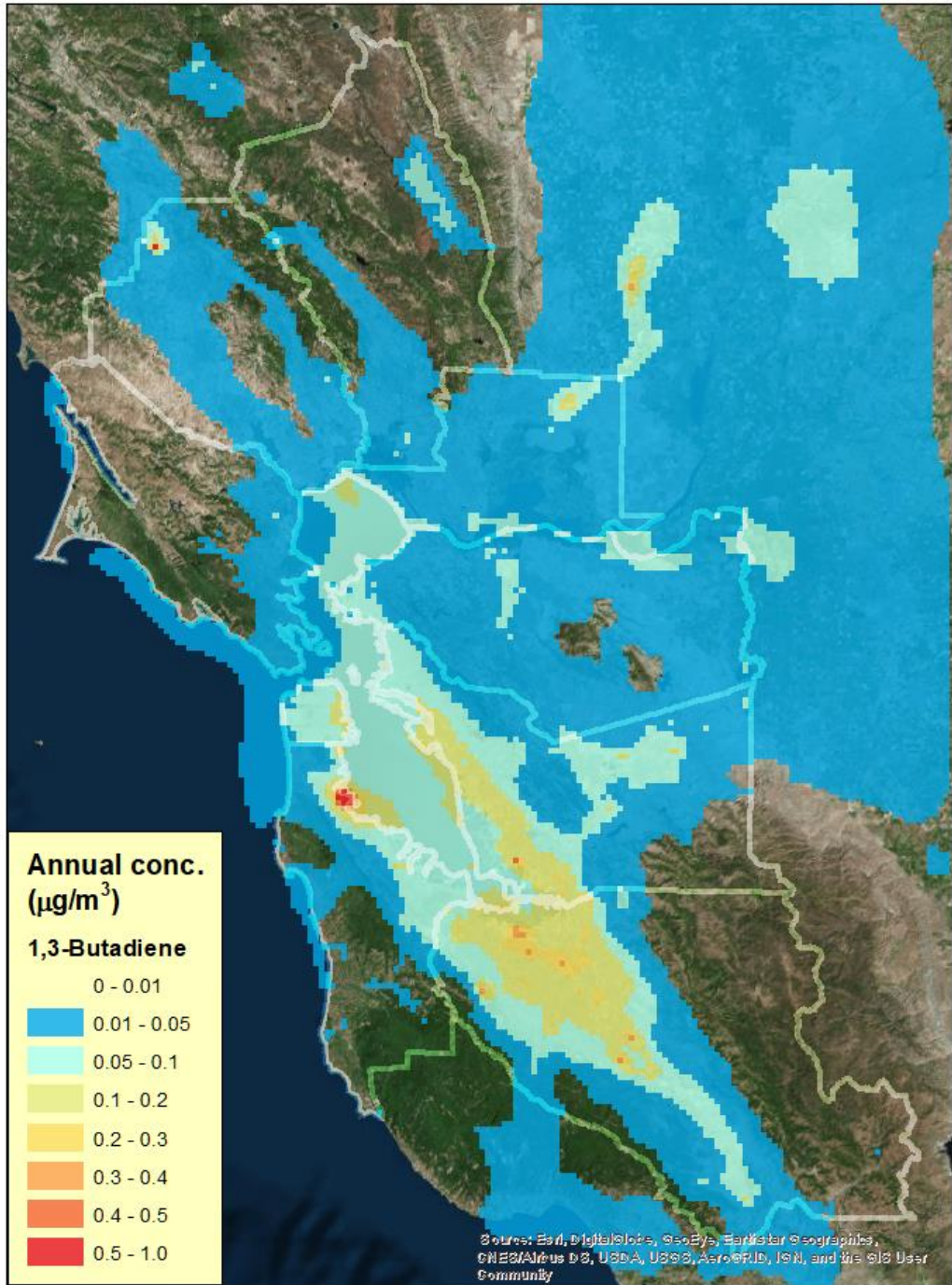
Maximum: 2.7

Figure 3.6: Annual average simulated acetaldehyde concentrations for 2016.



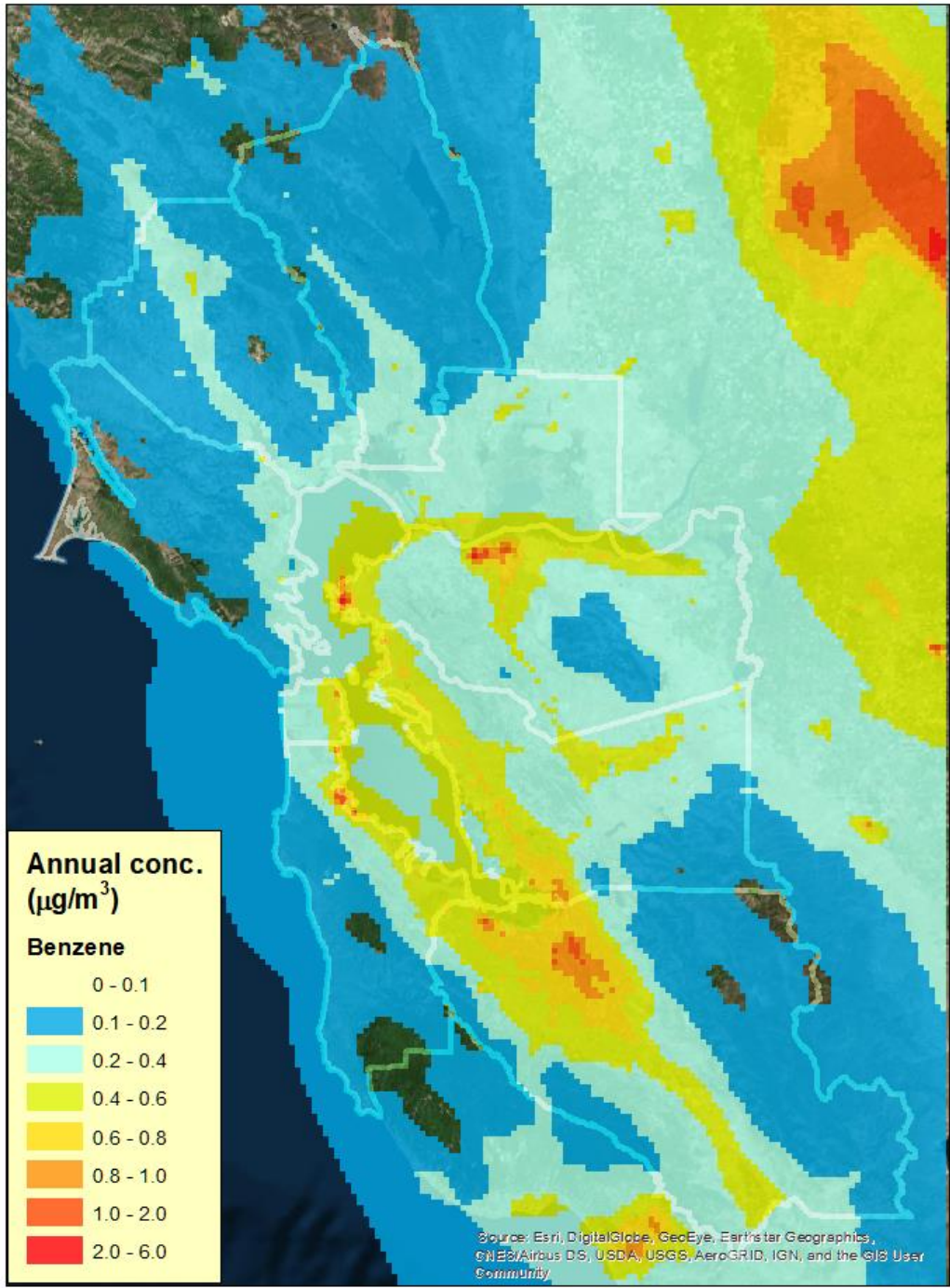
Maximum: 1.1

Figure 3.7: Annual average simulated acrolein concentrations for 2016.



Maximum: 0.9

Figure 3.8: Annual average simulated 1,3 butadiene concentrations for 2016.

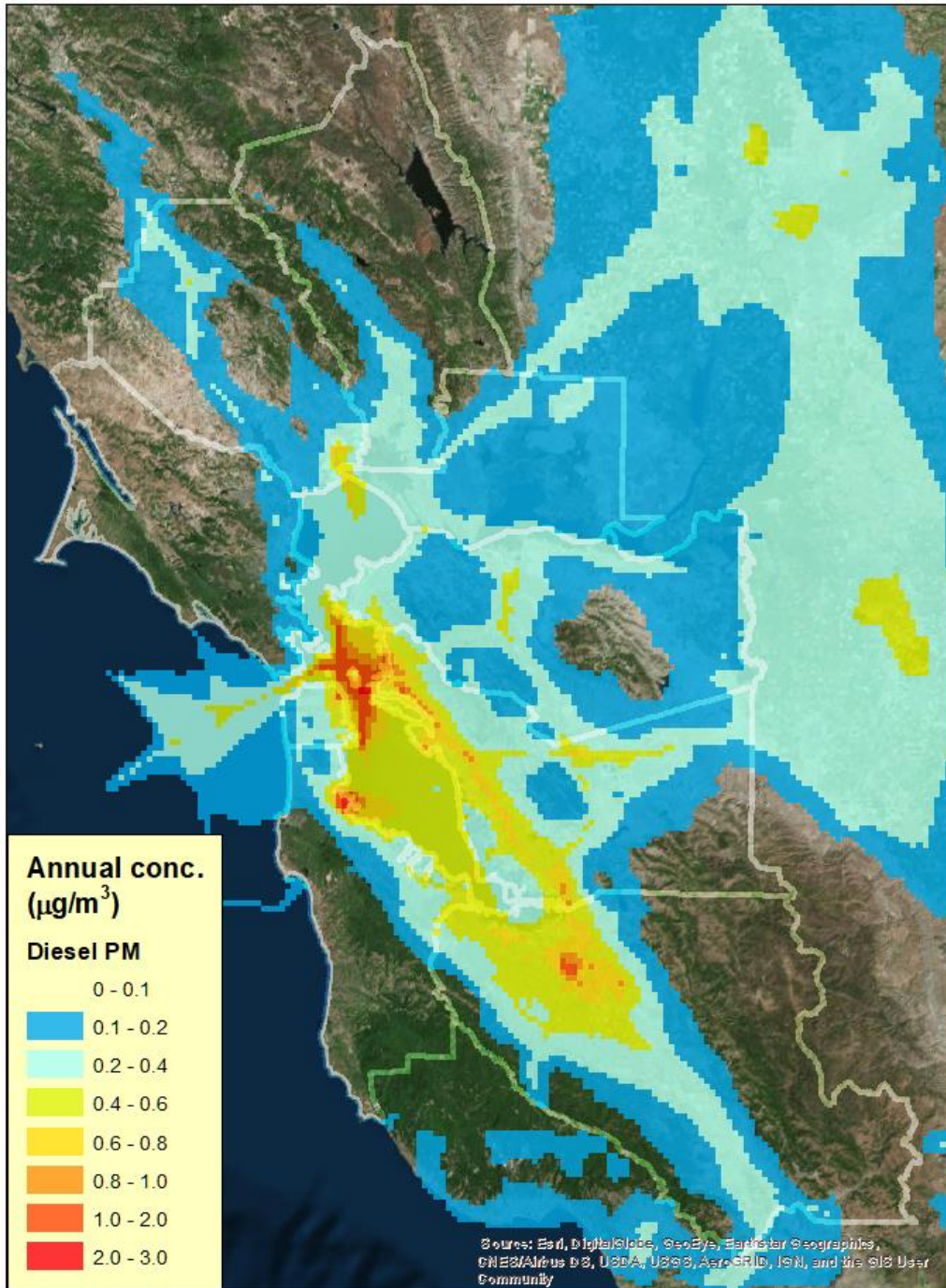


Maximum: 5.5

Figure 3.9: Annual average simulated benzene concentrations for 2016.

3.3.2 Diesel PM

Figure 3.10 shows the annual average concentrations of diesel PM. The highest concentration is $2.7 \mu\text{g}/\text{m}^3$ at San Francisco International Airport. Concentrations are also high (above $1 \mu\text{g}/\text{m}^3$) along the Bay Area ship routes, peaking at $2.6 \mu\text{g}/\text{m}^3$ near Yerba Buena Island, as well as in downtown Oakland and San Jose International Airport. Concentrations at Oakland International Airport reach $0.9 \mu\text{g}/\text{m}^3$. Concentrations along I-880 between Oakland and San Jose range mostly from 0.6 to $0.8 \mu\text{g}/\text{m}^3$ with some grid cells having concentrations above $0.8 \mu\text{g}/\text{m}^3$. The northern edge of San Pablo Bay, a portion of I-580 around Dublin, the Dumbarton Bridge, and a portion of US 101 north of Sunnyvale also show concentrations of 0.6 to $0.8 \mu\text{g}/\text{m}^3$.



Maximum: 2.7

Figure 3.10: Simulated annual average diesel PM concentrations for 2016.

3.3.3 Toxic Metals

Five toxic metals (hexavalent chromium, cadmium, lead, nickel, and mercury) were simulated, and their annual average concentrations were estimated. Emission estimates for these metals were taken from the EPA's 2014 National Air Toxics Assessment (NATA) inventory and may not

be representative of Bay Area emission levels for 2016. Therefore, the estimated annual average concentrations are considered to be preliminary. A summary of simulated metal concentrations is presented in Appendix C.

4. Model Performance Evaluation

The simulated air toxics concentrations were compared against available observations for the purpose of evaluating the CMAQ model. The District collects ambient air toxics data at 20 air monitoring stations, as discussed in Section 2.1. Locations of these stations are shown Figure 4.1. Samples of elemental carbon (EC) were used as a surrogate for evaluating diesel PM since diesel PM cannot be directly distinguished in the measurements.

Figure 4.2 shows scatter plots of observed vs. modeled formaldehyde and acetaldehyde concentrations at the San Jose-Jackson Street air monitoring station. The model tends to underestimate concentrations of these species but shows reasonable agreement with observations, aside from a few outliers.

Figure 4.3 shows scatter plots of observed vs. modeled benzene and 1,3-butadiene at the 20 toxics monitoring sites. Again, the model performance is reasonable but with slight underestimation. The underestimation biases at Oakland West are somewhat higher than the overall biases across all 20 sites, but agreement between the model and observations is still reasonable.

Figure 4.4 presents scatter plots of observed EC vs. modeled diesel PM. At Oakland West and San Jose-Jackson Street, modeled diesel PM concentrations are generally higher than observed EC. Assuming the predominant source of observed EC is diesel exhaust, this is expected because simulated diesel PM consists of PM components other than EC (e.g., organic carbon).

The modeled diesel PM tends to be lower than observed EC at Vallejo and Livermore, especially in winter and fall, suggesting EC sources other than diesel exhaust are influencing these sites (e.g., wood smoke). These discrepancies are also an indication of pollutant transport from outside the region defined in the modeling domain. While observations included the impact of such transport, the modeled concentrations did not because no diesel PM concentrations are specified along the model boundary. Overall, modeled diesel PM and observed EC are close enough to demonstrate their correlation.

Figure 4.5 compares observed and modeled concentrations of nickel, cadmium, lead and particulate-bound mercury. The model greatly underestimates the observed metal concentrations, indicating substantial uncertainty in emissions estimates for metals. This finding indicates that modeled cancer risks associated with toxic metals are also underestimated.

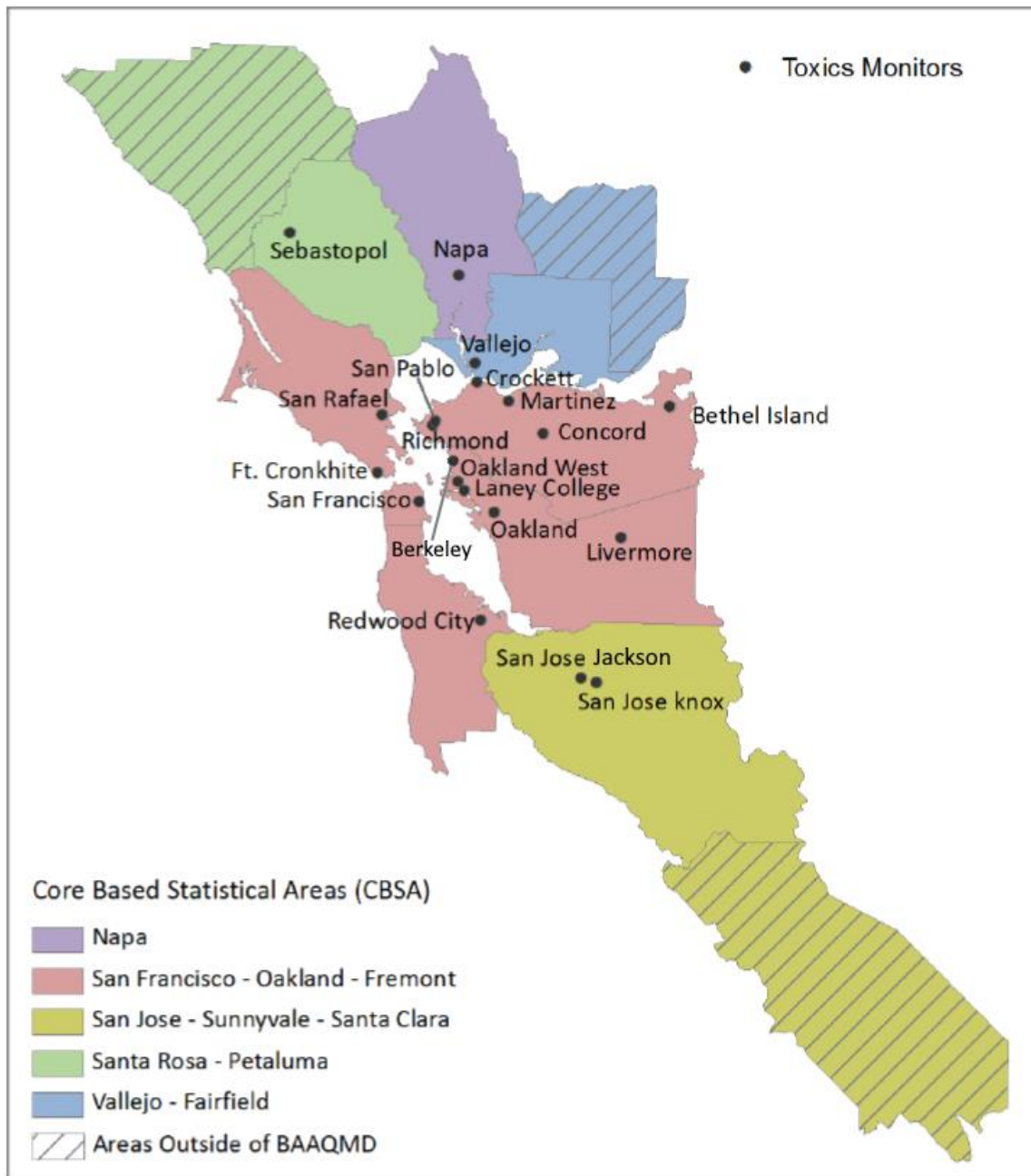
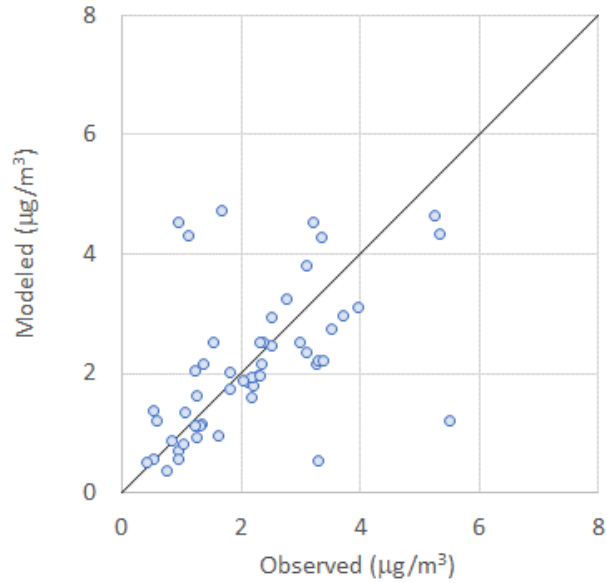


Figure 4.1: Map of BAAQMD toxics monitoring sites in 2016; reprinted from Knoderer et al. (2017). The location of the Berkeley site, which began operation on July 1, 2016, was added.

(a) Formaldehyde

NMB	-1.8%
NME	35%



(b) Acetaldehyde

NMB	-31%
NME	46%

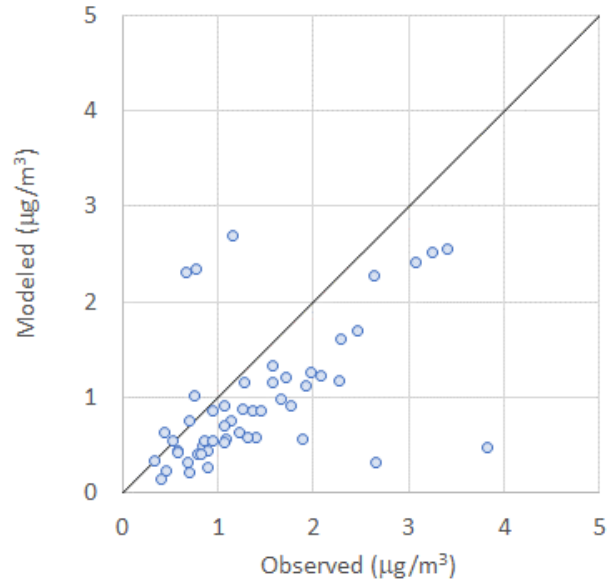


Figure 4.2: Observed vs. modeled 24-hr average concentrations of formaldehyde and acetaldehyde at the San Jose-Jackson St. site. Performance statistics shown are normalized mean bias (NMB) and normalized mean error (NME).

(a) Benzene

	All Sites	Oakland West
NMB	-16%	-29%
NME	40%	34%

(b) 1,3-butadiene

	All Sites	Oakland West
NMB	-5.7%	-28%
NME	44%	36%

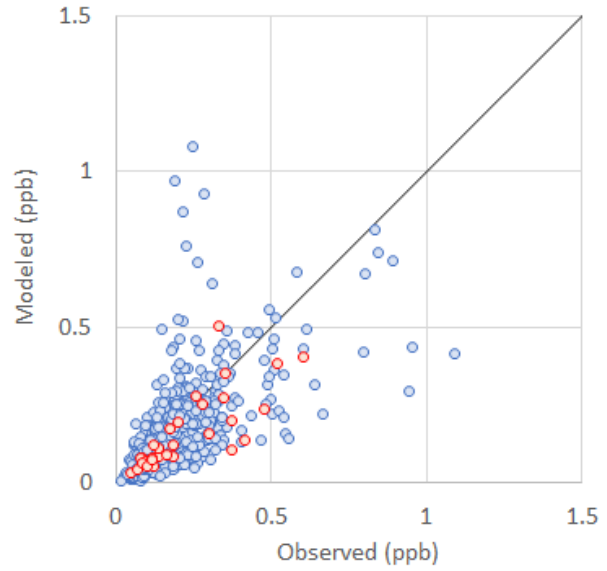
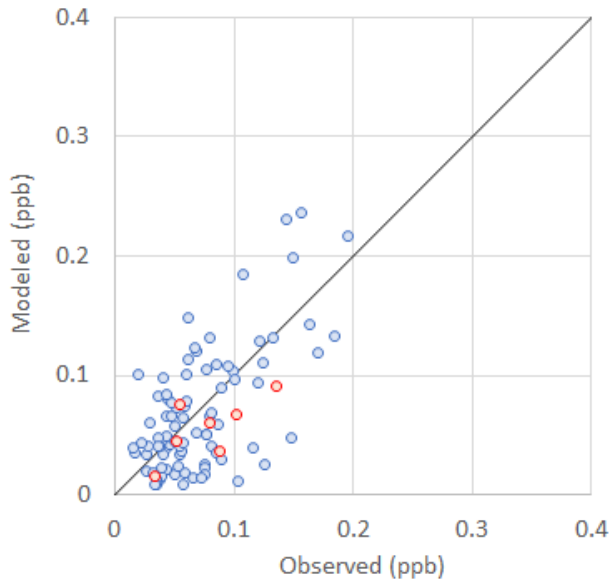


Figure 4.3: Observed vs. modeled 24-hr average concentrations of benzene and 1,3-butadiene at 20 toxics monitoring sites (values at the Oakland West site are shown in red). Normalized mean bias (NMB) and normalized mean error (NME) were calculated over all 20 sites, as well as at the Oakland West site alone.

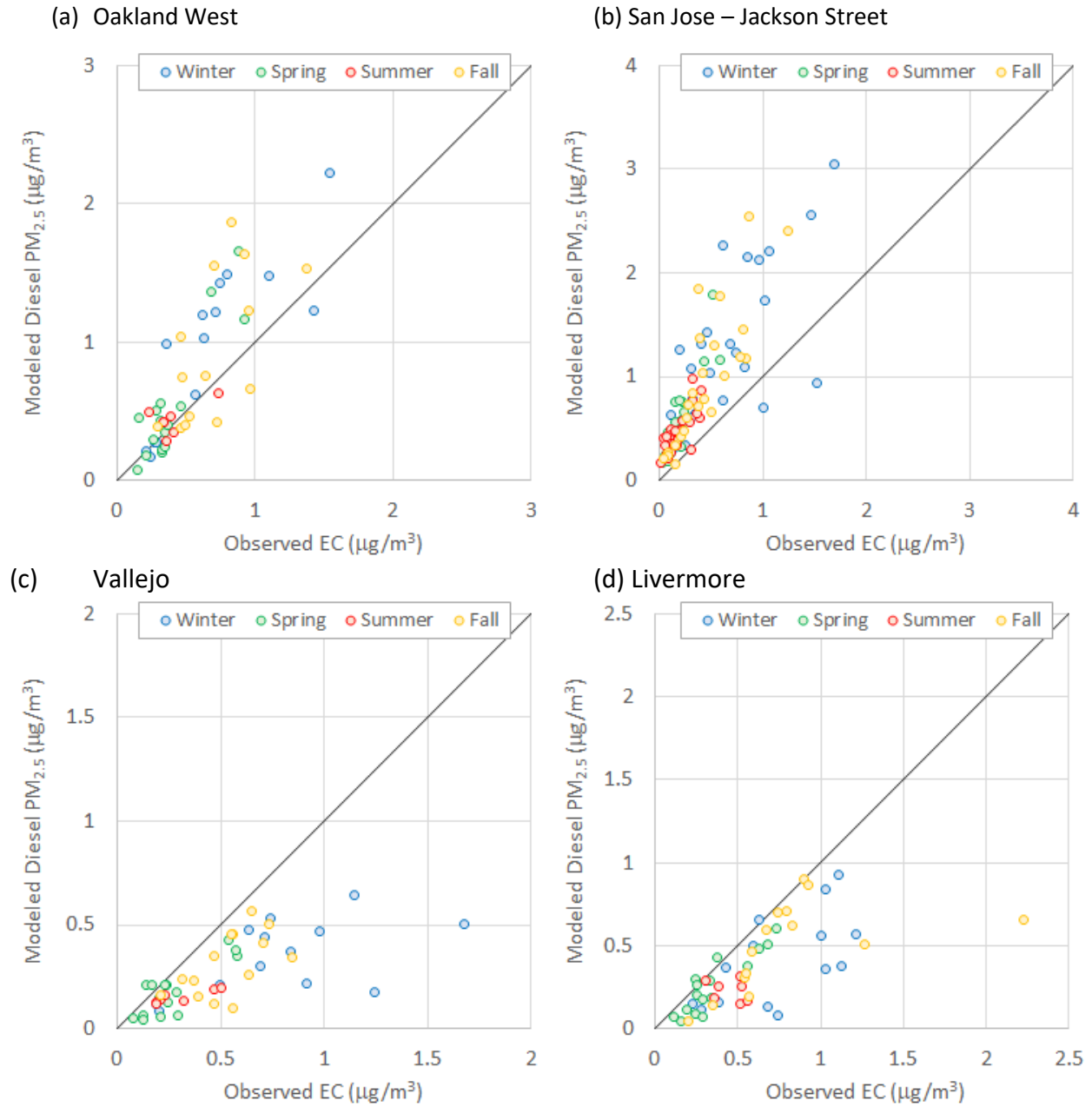
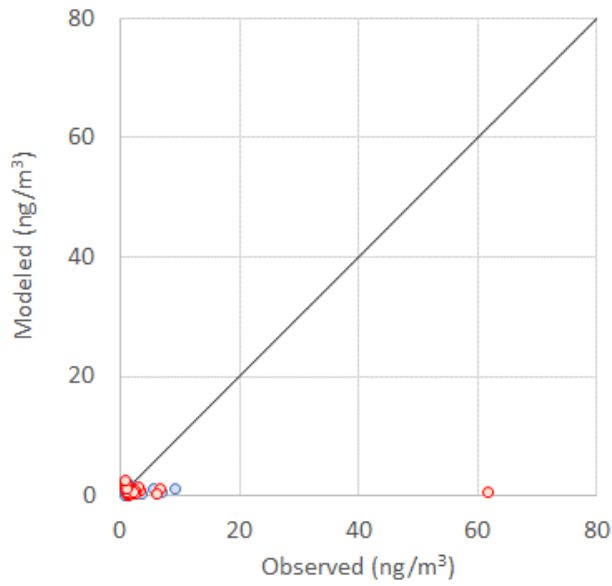
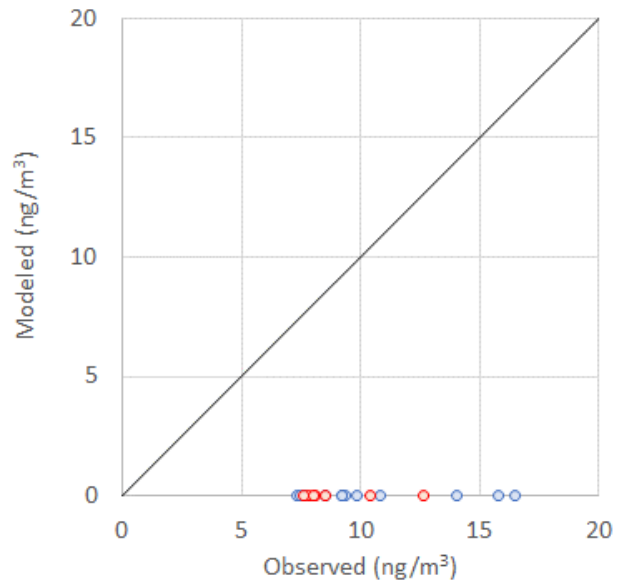


Figure 4.4: 24-hr average concentrations of observed PM_{2.5} EC vs. modeled diesel PM_{2.5} at Oakland West, San Jose-Jackson St., Vallejo and Livermore. Winter, spring, summer, and fall are defined as January-February-December, March-April-May, June-July-August, and September-October-November, respectively.

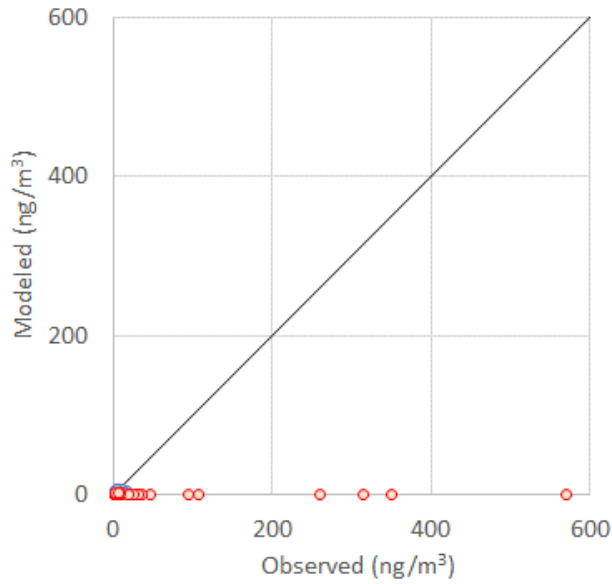
(a) Nickel



(b) Cadmium



(c) Lead



(d) Particulate bound mercury

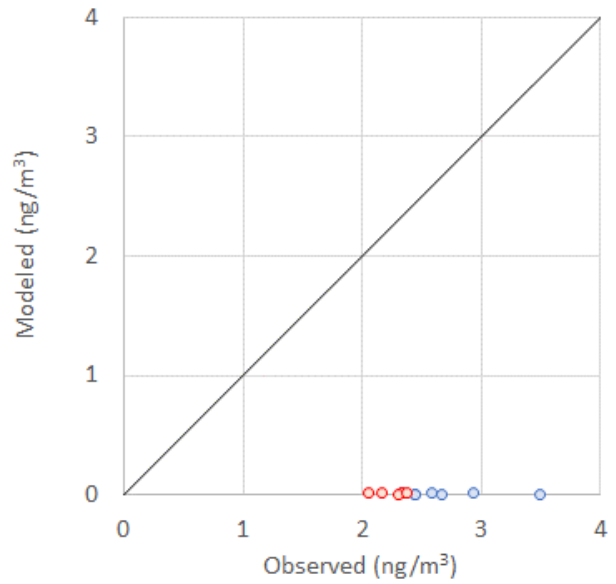


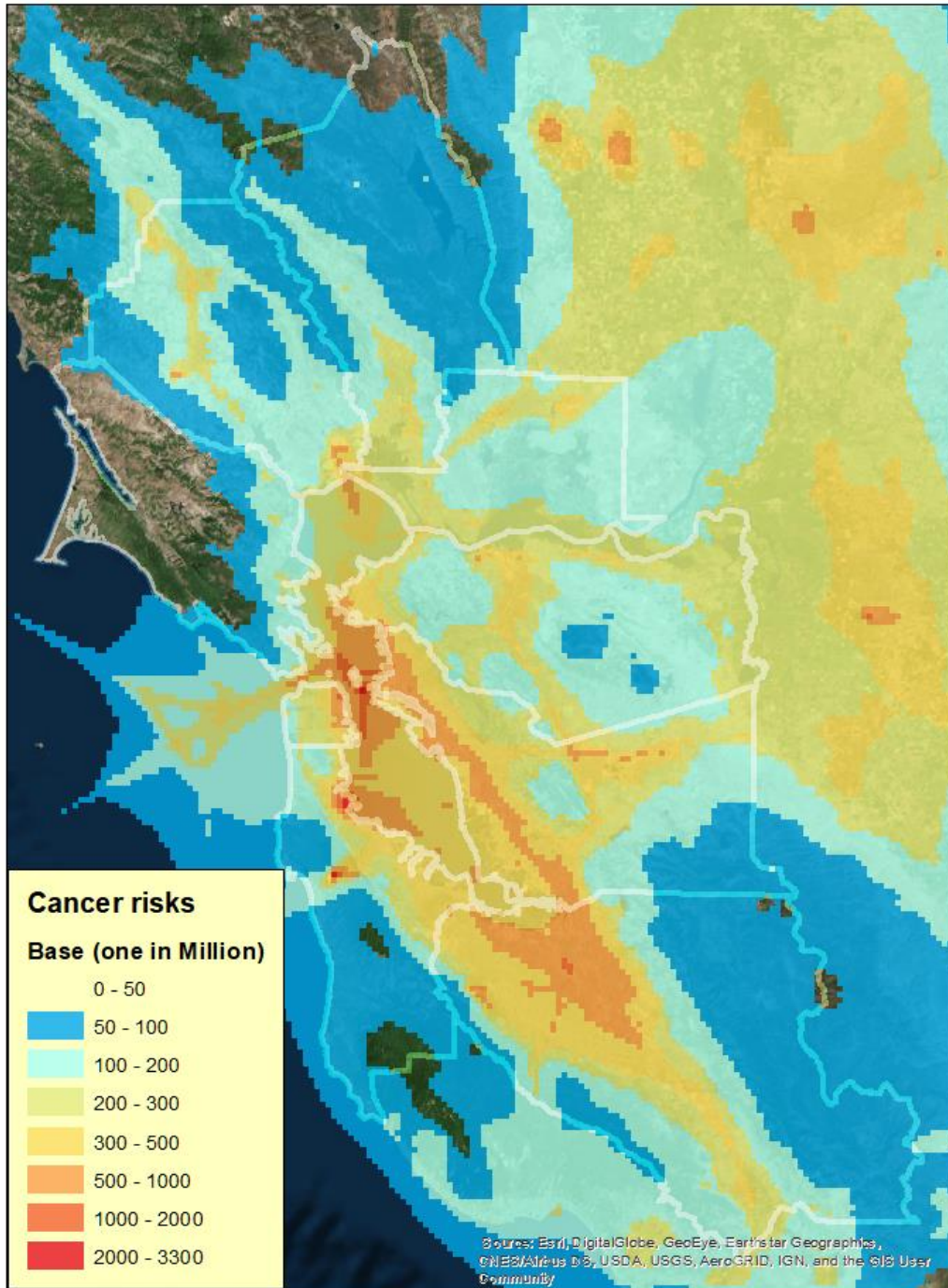
Figure 4.5: Observed vs. modeled 24-hr average concentrations of PM_{2.5} nickel, cadmium, lead and mercury at Oakland West, Vallejo, Livermore, and San Jose-Jackson St. (values at the Oakland West site are shown in red).

5. Risk Evaluation

As described in Section 1.1, cancer risk estimates for the modeled air toxics were calculated using inhalation unit risk factors. Cancer risk associated with modeled air toxics was calculated by multiplying annual average concentrations of each air toxic compound with its respective unit risk factor (Table 1.1) and then the resulting values were summed. The results were expressed as the number of expected excess cancer incidences per million people and are shown in Figure 5.1.

The highest number of estimated excess cancer incidences are modeled to occur east of Half Moon Bay (around 3,200 per million) which coincides with the location having the highest concentration of hexavalent chromium.³ Other than that, the spatial distribution of cancer risk in the Bay Area is similar to that of diesel PM concentrations (Figure 3.10), with the next highest cancer risks occurring at the San Francisco International Airport (about 2,600 per million). The number of estimated excess cancer incidences ranges from 1,000 to 2,000 per million at San Jose International Airport as well as in the area surrounding San Francisco International Airport. The excess cancer incidence estimates along the I-880 corridor connecting Oakland and San Jose, and along the US-101 corridor between San Jose and Palo Alto range from 500 to 1,000 per million.

³ The largest source of hexavalent chromium emissions in the emissions inventory is mineral processes, an area source that is spatially distributed based on the location of sand and gravel facilities.



Maximum: 3210

Figure 5.1: Expected excess cancer incidences per million.

6. Summary and Discussion

A total of 11 air toxics were simulated for 2016 over the entire Bay Area using the US EPA's CMAQ model at 1-km grid. Toxic included diesel particulate matter (DPM), 5 toxic gases (acetaldehyde, acrolein, benzene, 1,3-butadiene, and formaldehyde), and 5 trace metals (cadmium, chromium VI, lead, mercury, and nickel). Excess cancer risks were estimated for individual air toxics species as well as for all species combined. Previous analyses have indicated that DPM and the 5 toxic gases cumulatively account for more than 90% of toxic air contaminant emissions in the Bay Area (Tanrikulu et al., 2011).

Toxics measurement stations are sparsely distributed in the Bay Area, and samples are collected on a schedule of either 1 in 6 days or 1 in 12 days. A significant number of toxics measurements are below the instrument minimum detection limit, which makes it difficult to develop a conceptual model of air toxics formation and transport in the Bay Area. Nevertheless, comparisons between simulated and the available observed concentrations show reasonable agreement.

The District simulated DPM and the same five toxics gases for 2005 (Tanrikulu et al., 2009) and with projected emissions for 2015 (Tanrikulu et al., 2011) and estimated associated excess cancer risk. Both simulations were performed with the Comprehensive Air Quality Model with Extensions (CAMx). Because of limited computational resources, the prior simulations were conducted for only 2 weeks in January and 2 weeks in August.

Findings of this recent simulation were compared against the previous simulations and the recent simulations are determined to be improved estimates. Comparison between the new and old simulations, however, was not discussed in this report because the old simulations did not cover the entire year and their emission estimates relied on an older version of air toxics speciation.

Future related work includes updates to the spatial distribution of emissions data and to estimates of residential woodburning emissions. Recent PM modeling (Tanrikulu et al., 2019) showed that woodburning emissions may be significantly underestimated in the North Bay. As a result, concentrations of EC, formaldehyde and acetaldehyde, as well as associated cancer risk, may be underestimated.⁴

⁴ Note that the CMAQ modeling does not account for emissions from wildfires, which also have health impacts. However, the episodic and variable nature of these emissions present challenges for evaluating long-term exposures.

7. References

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Appendix A – Toxics Emissions Inventory

This appendix provides additional information on the emissions inventory used for the 2016 air toxics modeling, including summary tables and emissions density plots (note that tables and plots for DPM are provided in the main body of the report).

A1. Gaseous Species

Five gaseous air toxics were modeled explicitly in CMAQ: acetaldehyde, acrolein, benzene, 1,3-butadiene, and formaldehyde. Tables A1 through A5 show emissions of these species by geographic area and source sector. Figures A1 through A5 show the spatial distribution of these species across the 1-km modeling domain.

Table A1: Summary of 2016 acetaldehyde emissions (tons/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.04	0.08	0.30	0.03	0.45
Contra Costa	0.03	0.04	0.14	0.02	0.23
Marin	0.01	0.02	0.03	0.00	0.06
Napa	0.00	0.01	0.03	0.00	0.05
San Francisco	0.02	0.09	0.07	0.00	0.18
San Mateo	0.02	0.19	0.07	0.02	0.29
Santa Clara	0.04	0.06	0.23	0.02	0.35
Solano	0.01	0.04	0.06	0.01	0.11
Sonoma	0.01	0.03	0.08	0.00	0.12
<i>BAAQMD Subtotal</i>	<i>0.18</i>	<i>0.55</i>	<i>1.01</i>	<i>0.09</i>	<i>1.84</i>
Non-BAAQMD Counties	0.13	0.16	0.69	0.45	1.44
Domain Total	0.31	0.72	1.71	0.54	3.28

Table A2: Summary of 2016 acrolein emissions (tons/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.03	0.02	0.03	0.05	0.13
Contra Costa	0.02	0.00	0.01	0.01	0.05
Marin	0.00	0.00	0.00	0.00	0.01
Napa	0.00	0.00	0.00	0.00	0.01
San Francisco	0.01	0.00	0.01	0.00	0.02
San Mateo	0.01	0.08	0.01	0.01	0.11
Santa Clara	0.02	0.02	0.02	0.01	0.06
Solano	0.01	0.02	0.00	0.01	0.03
Sonoma	0.01	0.00	0.01	0.00	0.02
<i>BAAQMD Subtotal</i>	<i>0.11</i>	<i>0.14</i>	<i>0.09</i>	<i>0.09</i>	<i>0.43</i>
Non-BAAQMD Counties	0.04	0.02	0.06	0.11	0.23
Domain Total	0.15	0.16	0.15	0.20	0.66

Table A3: Summary of 2016 benzene emissions (tons/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.19	0.10	0.39	0.20	0.89
Contra Costa	0.20	0.08	0.25	0.49	1.01
Marin	0.03	0.04	0.08	0.03	0.18
Napa	0.03	0.02	0.04	0.01	0.10
San Francisco	0.06	0.05	0.09	0.02	0.22
San Mateo	0.09	0.11	0.15	0.09	0.43
Santa Clara	0.21	0.11	0.40	0.26	0.98
Solano	0.05	0.03	0.08	0.07	0.23
Sonoma	0.05	0.03	0.11	0.01	0.21
<i>BAAQMD Subtotal</i>	<i>0.90</i>	<i>0.57</i>	<i>1.60</i>	<i>1.19</i>	<i>4.25</i>
Non-BAAQMD Counties	0.96	0.30	0.90	5.57	7.73
Domain Total	1.86	0.87	2.50	6.76	11.99

Table A4: Summary of 2016 1,3-butadiene emissions (tons/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.07	0.10	0.04	0.05	0.25
Contra Costa	0.02	0.08	0.02	0.02	0.14
Marin	0.00	0.04	0.01	0.00	0.05
Napa	0.00	0.03	0.00	0.01	0.04
San Francisco	0.01	0.05	0.01	0.00	0.07
San Mateo	0.01	0.10	0.01	0.02	0.14
Santa Clara	0.14	0.10	0.04	0.03	0.30
Solano	0.01	0.03	0.01	0.01	0.05
Sonoma	0.01	0.03	0.01	0.02	0.07
<i>BAAQMD Subtotal</i>	<i>0.28</i>	<i>0.56</i>	<i>0.14</i>	<i>0.15</i>	<i>1.13</i>
Non-BAAQMD Counties	0.08	0.20	0.08	0.20	0.56
Domain Total	0.36	0.76	0.22	0.35	1.69

Table A5: Summary of 2016 formaldehyde emissions (tons/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.09	0.24	0.22	0.68	1.23
Contra Costa	0.19	0.12	0.11	1.79	2.21
Marin	0.02	0.05	0.03	0.06	0.16
Napa	0.01	0.04	0.02	0.07	0.14
San Francisco	0.05	0.25	0.05	0.20	0.54
San Mateo	0.06	0.60	0.06	0.18	0.88
Santa Clara	0.10	0.19	0.18	1.02	1.49
Solano	0.07	0.12	0.04	0.10	0.33
Sonoma	0.03	0.08	0.06	0.32	0.48
<i>BAAQMD Subtotal</i>	<i>0.60</i>	<i>1.68</i>	<i>0.76</i>	<i>4.42</i>	<i>7.47</i>
Non-BAAQMD Counties	0.43	0.61	0.49	1.56	3.09
Domain Total	1.04	2.29	1.25	5.97	10.55

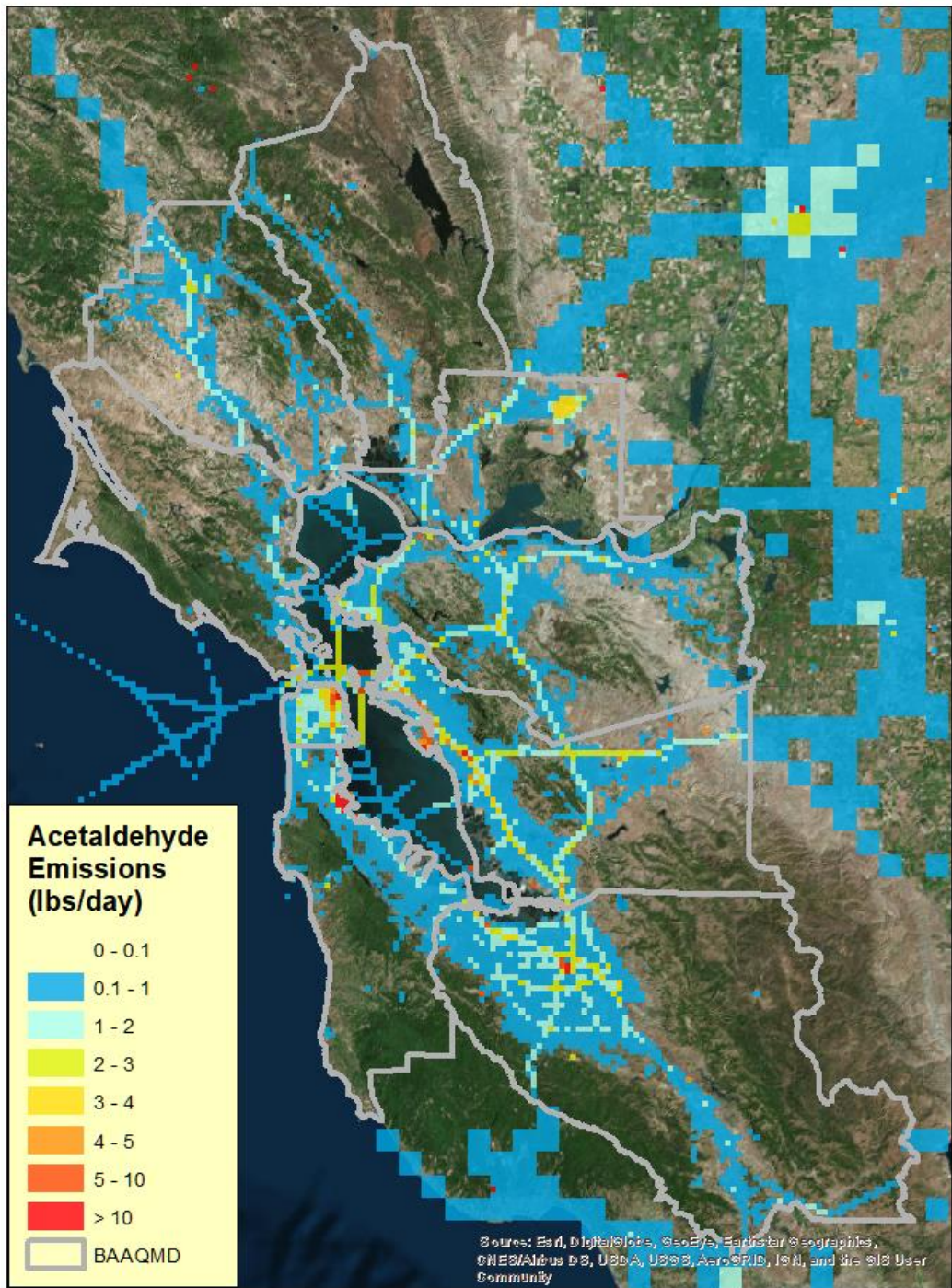


Figure A1: Spatial distribution of 2016 annual average acetaldehyde emissions for the 1-km modeling domain.

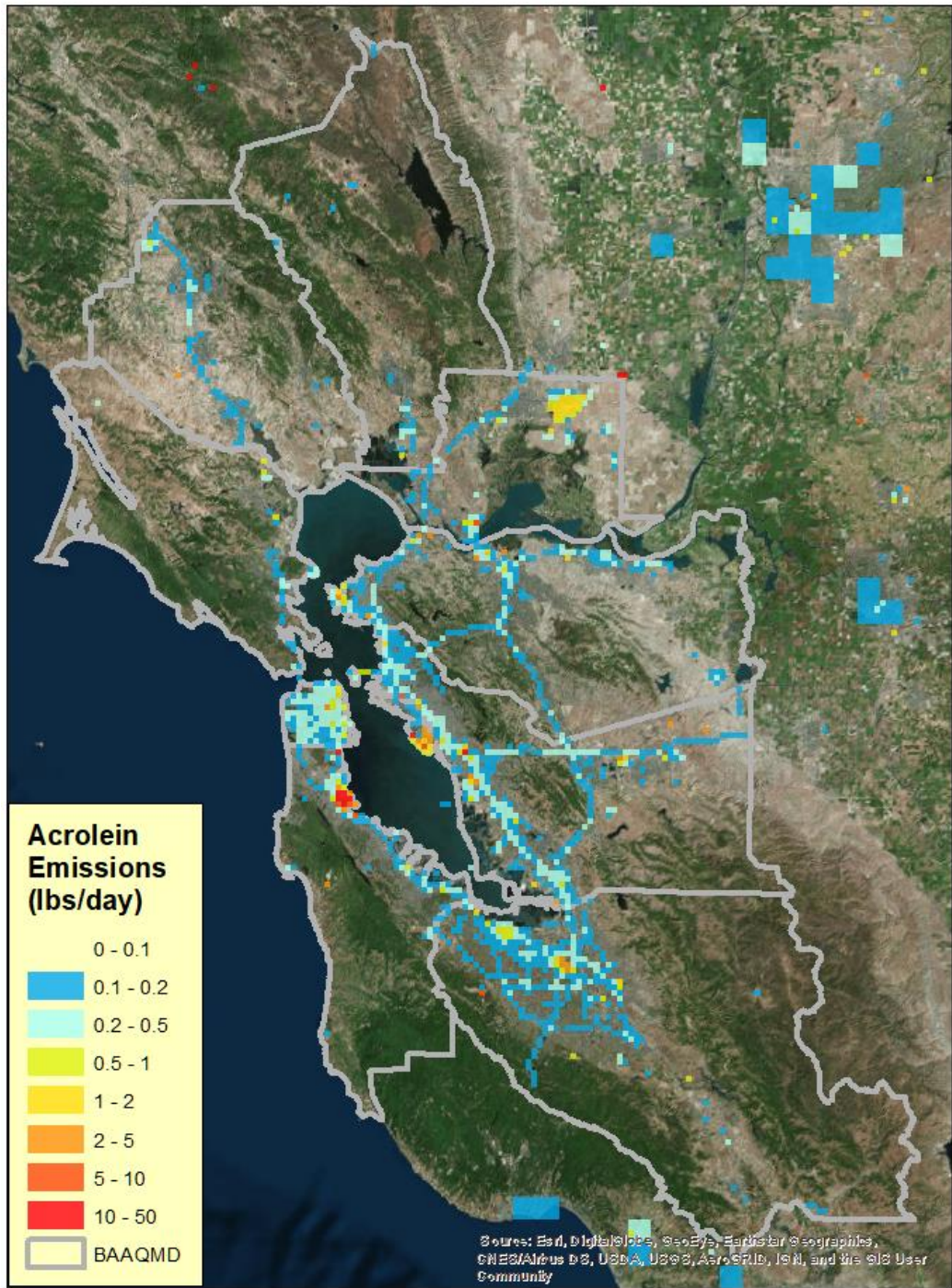


Figure A2: Spatial distribution of 2016 annual average acrolein emissions for the 1-km modeling domain.

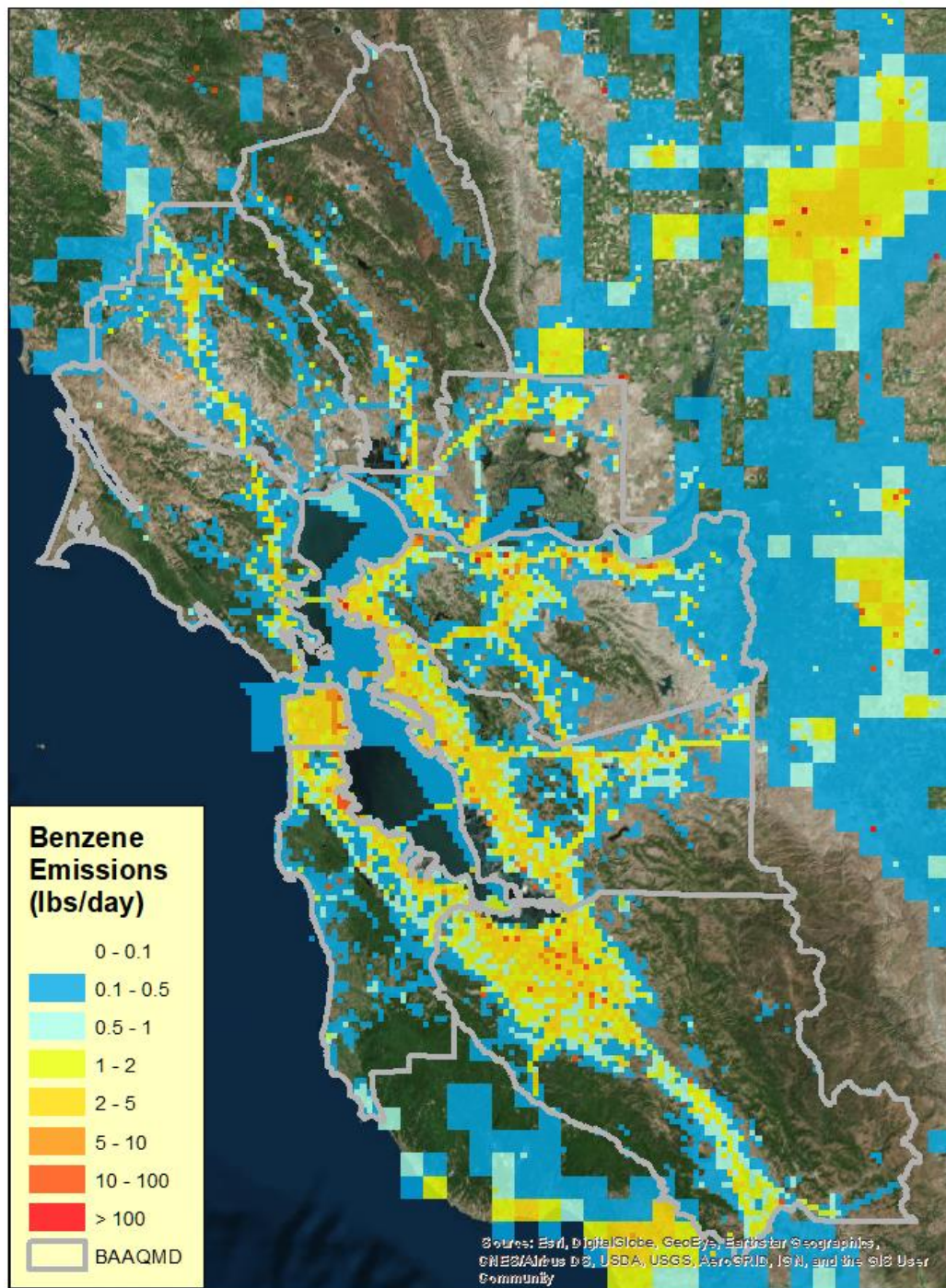


Figure A3: Spatial distribution of 2016 annual average benzene emissions for the 1-km modeling domain.

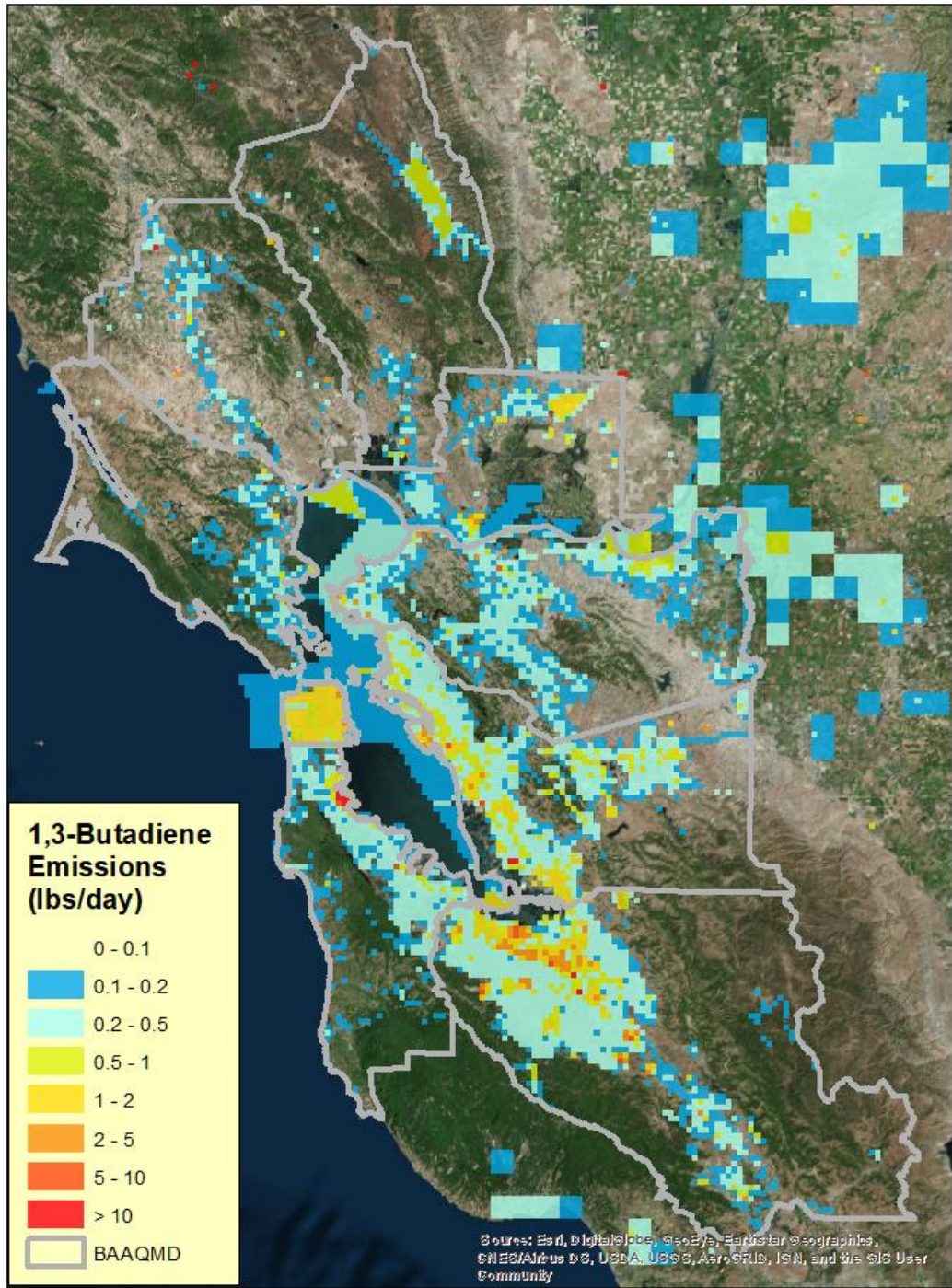


Figure A4: Spatial distribution of 2016 annual average 1,3-butadiene emissions for the 1-km modeling domain.

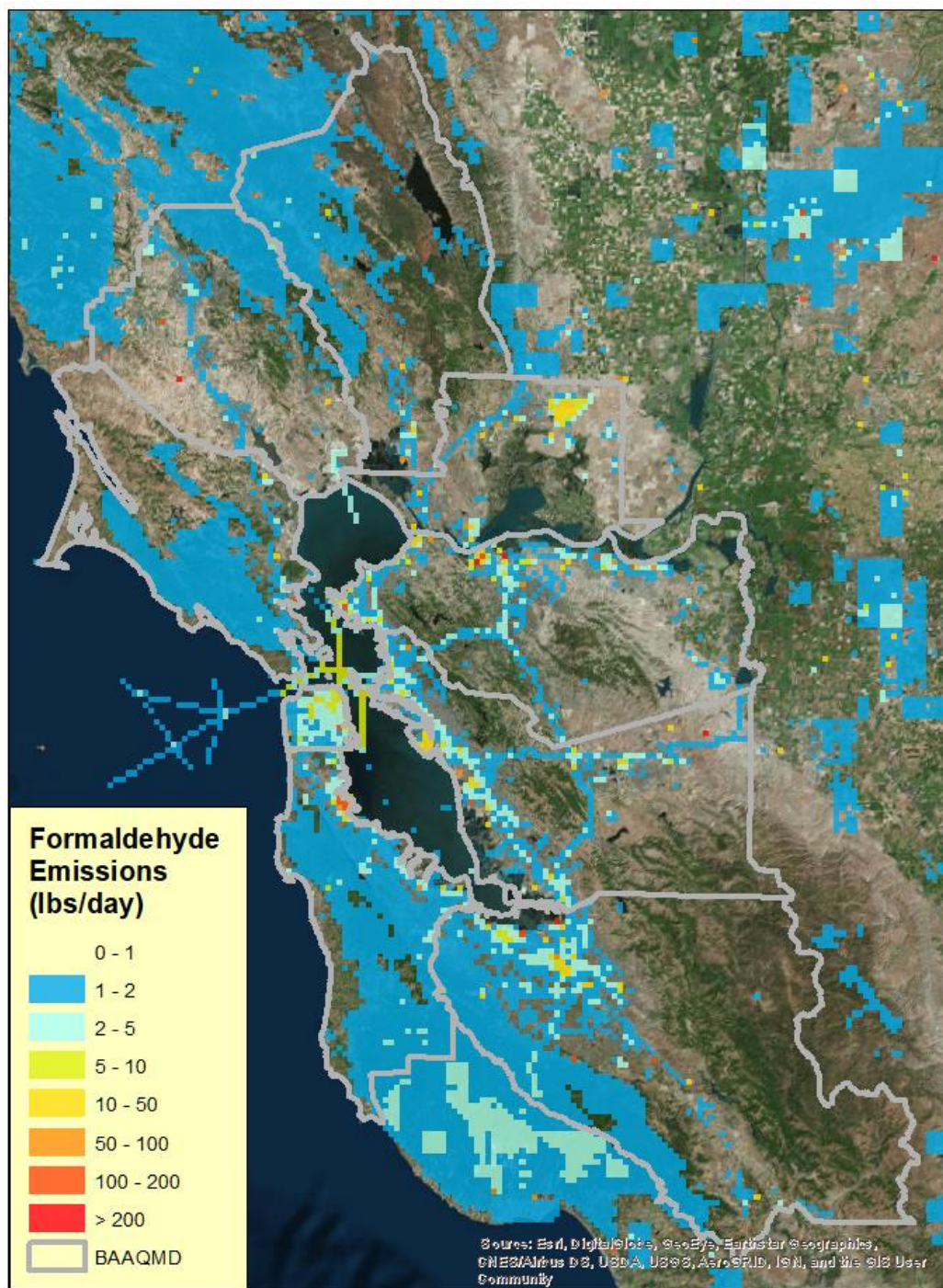


Figure A5: Spatial distribution of 2016 annual average formaldehyde emissions for the 1-km modeling domain.

A2. Trace Metals

Five trace metals were modeled explicitly in CMAQ: cadmium, chromium VI, lead, mercury, and nickel. Tables A6 through A10 show emissions of these species by geographic area and source

sector. Figures A6 through A10 show the spatial distribution of these species across the 1-km modeling domain.

Table A6: Summary of 2016 cadmium emissions (lbs/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.03	0.00	0.00	0.00	0.04
Contra Costa	0.03	0.00	0.00	0.01	0.05
Marin	0.01	0.00	0.00	0.00	0.01
Napa	0.01	0.00	0.00	0.00	0.01
San Francisco	0.02	0.02	0.00	0.00	0.04
San Mateo	0.02	0.00	0.00	0.00	0.02
Santa Clara	0.09	0.00	0.00	0.00	0.09
Solano	0.01	0.00	0.00	0.00	0.02
Sonoma	0.02	0.00	0.00	0.00	0.02
<i>BAAQMD Subtotal</i>	<i>0.24</i>	<i>0.04</i>	<i>0.00</i>	<i>0.02</i>	<i>0.29</i>
Non-BAAQMD Counties	0.13	0.01	0.00	0.16	0.31
Domain Total	0.36	0.05	0.00	0.19	0.60

Table A7: Summary of 2016 chromium VI emissions (lbs/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.05	0.00	0.01	0.00	0.07
Contra Costa	0.01	0.00	0.01	0.12	0.14
Marin	0.01	0.00	0.00	0.00	0.01
Napa	0.00	0.00	0.00	0.00	0.00
San Francisco	0.01	0.01	0.00	0.00	0.02
San Mateo	0.64	0.00	0.01	0.00	0.65
Santa Clara	0.35	0.00	0.01	0.01	0.37
Solano	0.00	0.00	0.00	0.02	0.03
Sonoma	0.15	0.00	0.00	0.00	0.15
<i>BAAQMD Subtotal</i>	<i>1.22</i>	<i>0.02</i>	<i>0.05</i>	<i>0.15</i>	<i>1.44</i>
Non-BAAQMD Counties	1.30	0.01	0.03	0.14	1.48
Domain Total	2.52	0.03	0.08	0.29	2.92

Table A8: Summary of 2016 lead emissions (lbs/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.39	0.00	0.00	5.93	6.33
Contra Costa	1.30	0.01	0.00	3.12	4.43
Marin	0.08	0.00	0.00	1.72	1.81
Napa	0.07	0.00	0.00	0.79	0.86
San Francisco	0.25	0.01	0.00	0.00	0.26
San Mateo	0.39	0.00	0.00	3.02	3.40
Santa Clara	0.71	0.00	0.00	6.11	6.82
Solano	0.17	0.00	0.00	2.20	2.38
Sonoma	0.17	0.00	0.00	1.84	2.01

<i>BAAQMD Subtotal</i>	3.53	0.02	0.00	24.73	28.29
Non-BAAQMD Counties	1.70	0.03	0.00	13.59	15.32
Domain Total	5.22	0.05	0.00	38.32	43.60

Table A9: Summary of 2016 mercury emissions (lbs/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.16	0.01	0.01	0.00	0.19
Contra Costa	0.08	0.01	0.00	0.15	0.24
Marin	0.02	0.00	0.00	0.00	0.02
Napa	0.01	0.00	0.00	0.00	0.02
San Francisco	0.06	0.01	0.00	0.00	0.07
San Mateo	0.06	0.00	0.00	0.00	0.06
Santa Clara	0.14	0.01	0.01	0.41	0.57
Solano	0.02	0.00	0.00	0.01	0.04
Sonoma	0.03	0.00	0.00	0.00	0.03
<i>BAAQMD Subtotal</i>	<i>0.58</i>	<i>0.05</i>	<i>0.04</i>	<i>0.57</i>	<i>1.25</i>
Non-BAAQMD Counties	0.18	0.04	0.02	0.07	0.31
Domain Total	0.76	0.09	0.06	0.65	1.56

Table A10: Summary of 2016 nickel emissions (lbs/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	1.79	1.41	2.51	0.05	5.76
Contra Costa	0.85	1.55	1.38	1.75	5.54
Marin	0.07	1.74	0.41	0.00	2.22
Napa	0.03	0.81	0.20	0.00	1.03
San Francisco	0.17	1.37	0.59	0.01	2.15
San Mateo	0.16	1.03	1.00	0.02	2.21
Santa Clara	1.45	1.16	2.45	0.10	5.16
Solano	0.07	0.73	0.47	1.12	2.39
Sonoma	0.28	0.67	0.45	0.00	1.41
<i>BAAQMD Subtotal</i>	<i>4.87</i>	<i>10.46</i>	<i>9.47</i>	<i>3.06</i>	<i>27.86</i>
Non-BAAQMD Counties	5.17	3.82	4.82	3.89	17.71
Domain Total	10.04	14.29	14.29	6.95	45.57

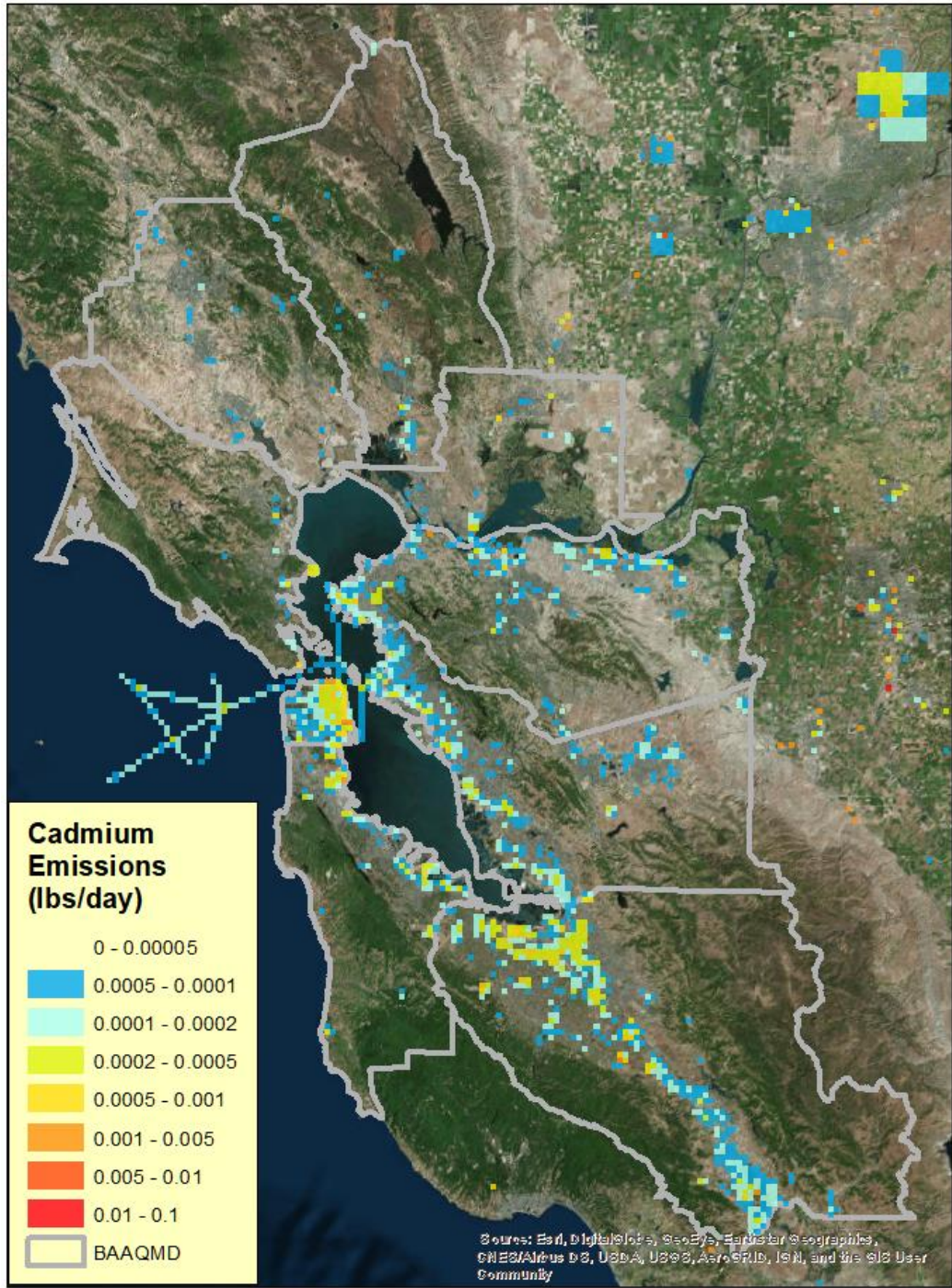


Figure A6: Spatial distribution of 2016 annual average cadmium emissions for the 1-km modeling domain.

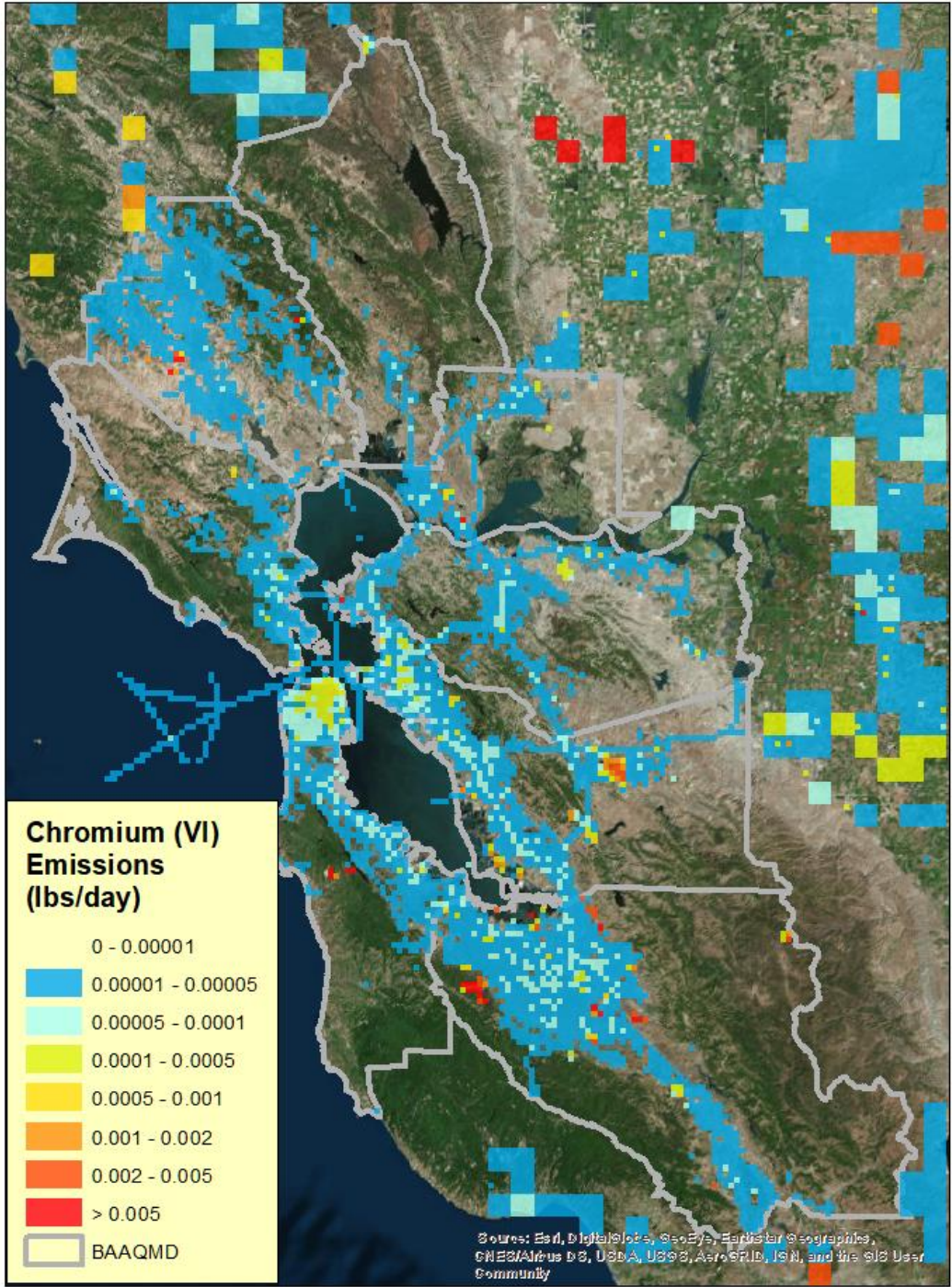


Figure A7: Spatial distribution of 2016 annual average chromium VI emissions for the 1-km modeling domain.

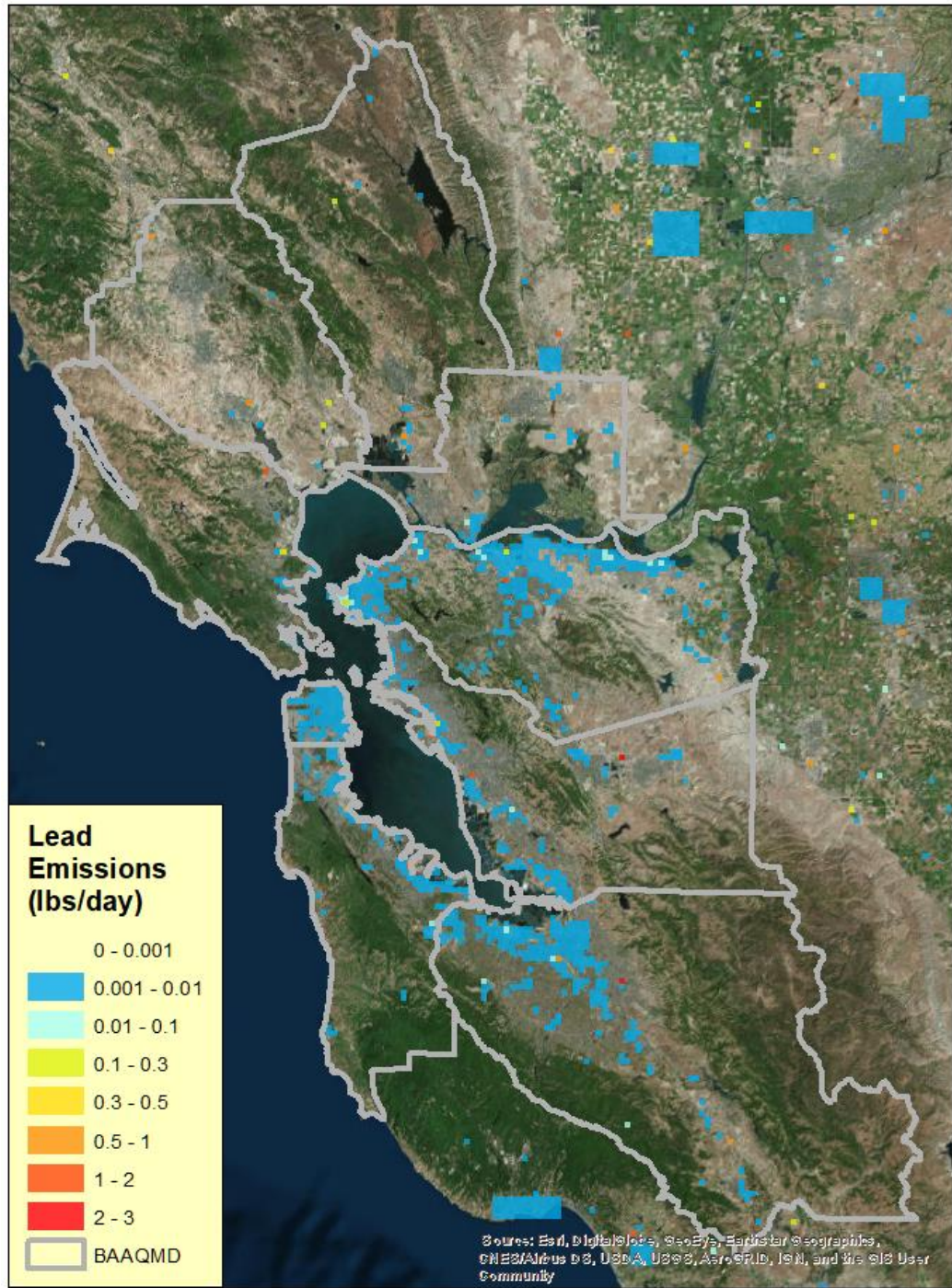


Figure A8: Spatial distribution of 2016 annual average lead emissions for the 1-km modeling domain.

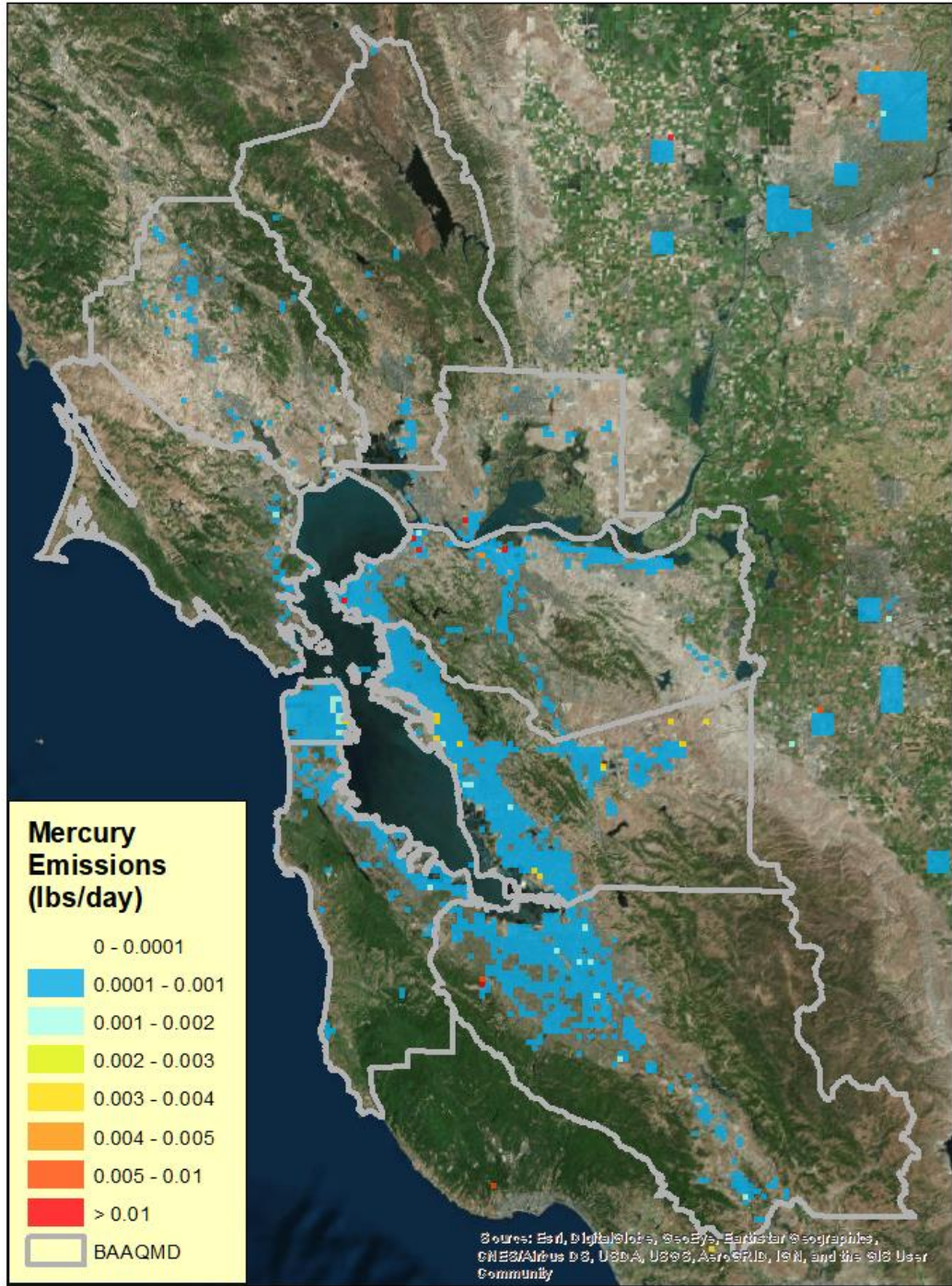


Figure A9: Spatial distribution of 2016 annual average mercury emissions for the 1-km modeling domain.

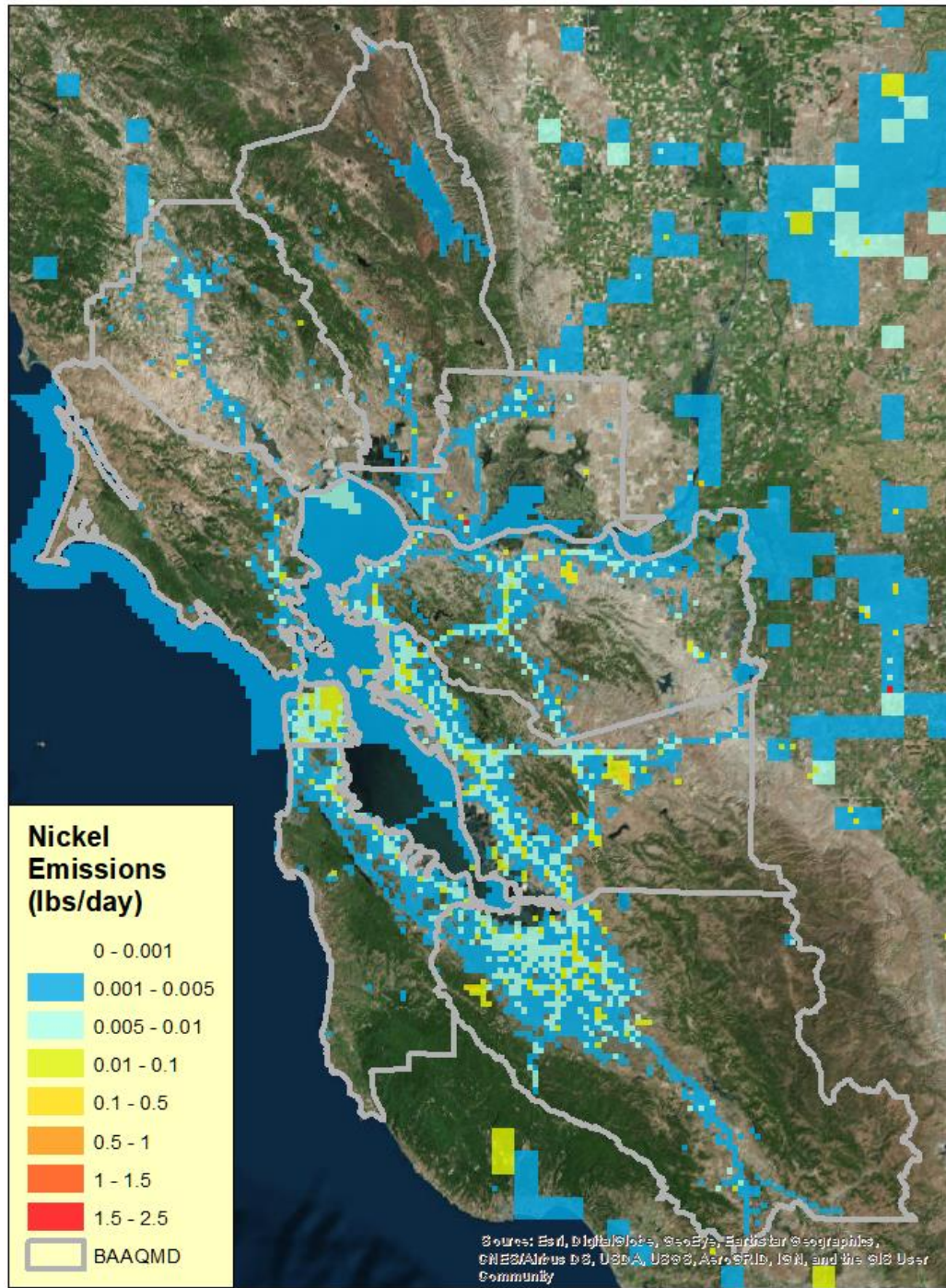


Figure A10: Spatial distribution of 2016 annual average nickel emissions for the 1-km modeling domain.

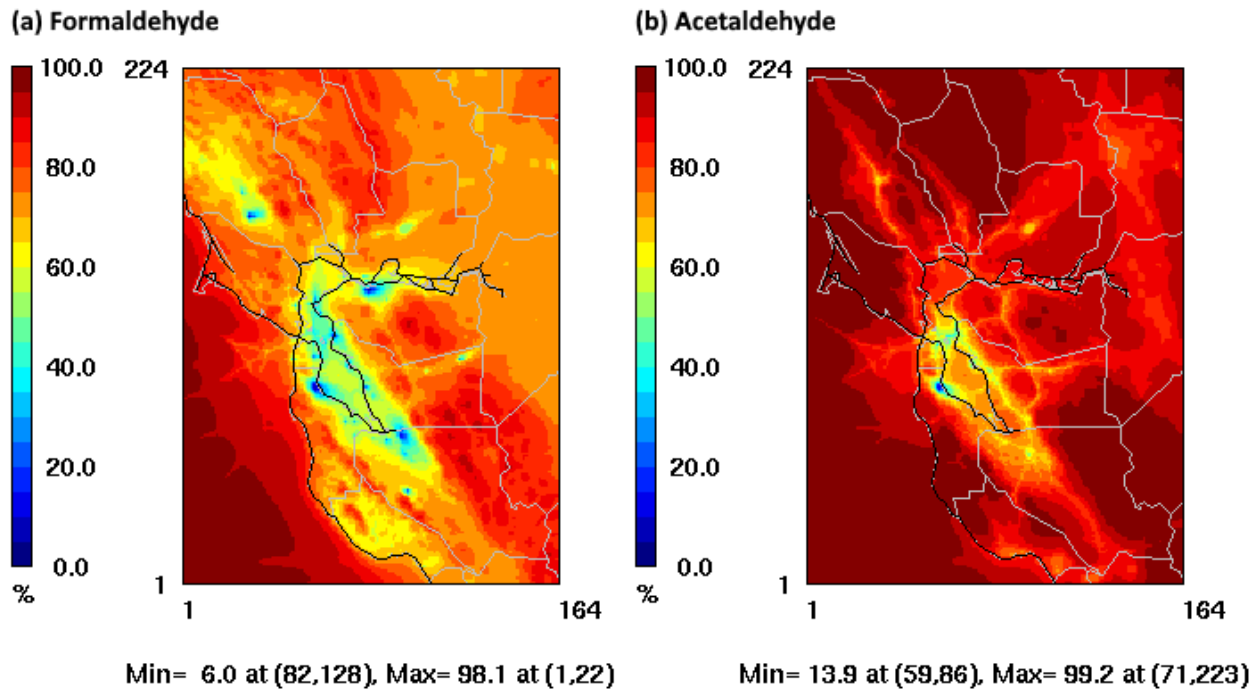
Appendix B: Simulated Primary vs Secondary Air Toxics

Some air toxic compounds have both primary components (i.e., direct emissions) and secondary components (i.e., production in the atmosphere via chemical reactions of other hydrocarbons). For example, formaldehyde and acetaldehyde are primarily formed from atmospheric oxidation of other biogenic (e.g., isoprene emitted from plants) and anthropogenic (e.g., ethene and propene from petrochemical facilities) VOCs. Acrolein is one of the major products of the photochemical oxidation of 1,3-butadiene.

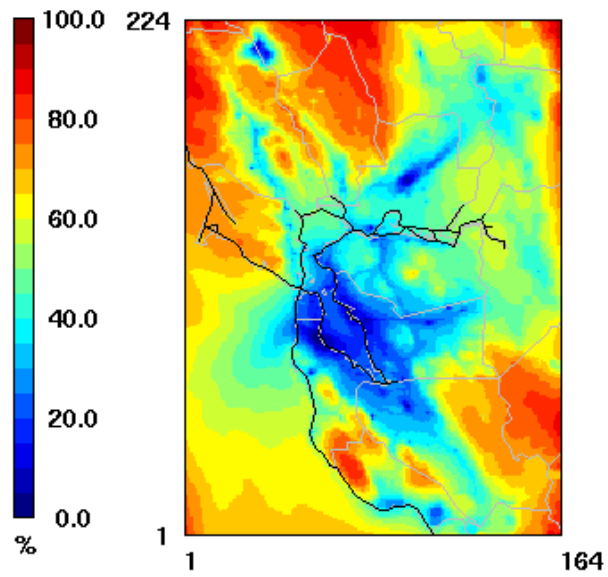
To assess the relative importance of the primary and secondary contributions, CMAQ's SAPRC07TC chemistry mechanism explicitly tracks primary emissions of formaldehyde, acetaldehyde and acrolein, as well as their photochemical production.

Figure B1 shows fractions of secondary contributions to annual average formaldehyde, acetaldehyde and acrolein concentrations in the 1-km modeling domain. Secondary production is the predominant source of formaldehyde and acetaldehyde in most areas of the modeling domain except in the immediate vicinity of emissions sources. Contributions of primary acrolein are generally higher than those of primary formaldehyde and acetaldehyde.

Figure B2 displays relative contributions of primary and secondary formaldehyde, acetaldehyde and acrolein over the West Oakland receptor domain. The primary contributions are relatively higher in this area, which indicates substantial local source influences.



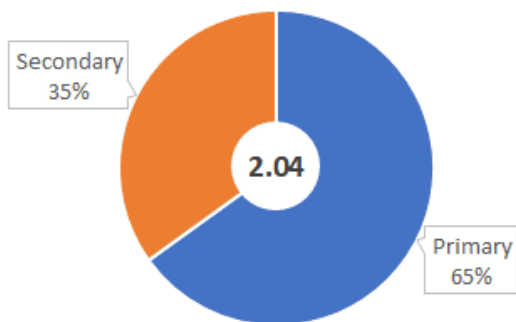
(c) Acrolein



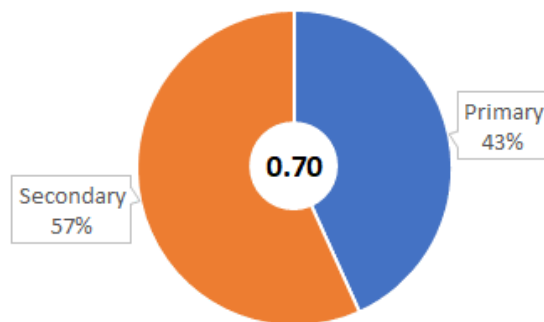
Min= 1.2 at (59,86), Max= 93.0 at (164,224)

Figure B1: Percent contributions of secondary production to annual average formaldehyde, acetaldehyde and acrolein concentrations in the 1-km modeling domain.

(a) Formaldehyde



(b) Acetaldehyde



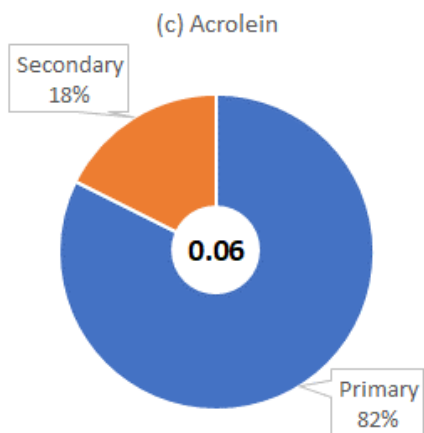


Figure B2: Percent contributions of secondary production to annual average formaldehyde, acetaldehyde and acrolein concentrations over the West Oakland Receptor domain. The numbers in the center represent total (primary plus secondary) concentrations.

Appendix C: Simulated Trace Metals

Figures C1 through C5 show the annual average concentrations of hexavalent chromium, cadmium, lead, nickel, and mercury, respectively. Mercury concentrations are shown as sum of all three forms of atmospheric mercury (gaseous elemental mercury, gaseous oxidized mercury, and particulate bound mercury). Note that the trace metal concentrations in these figures are given in nanograms per cubic meter (ng/m^3) to better represent their typical atmospheric concentration ranges.

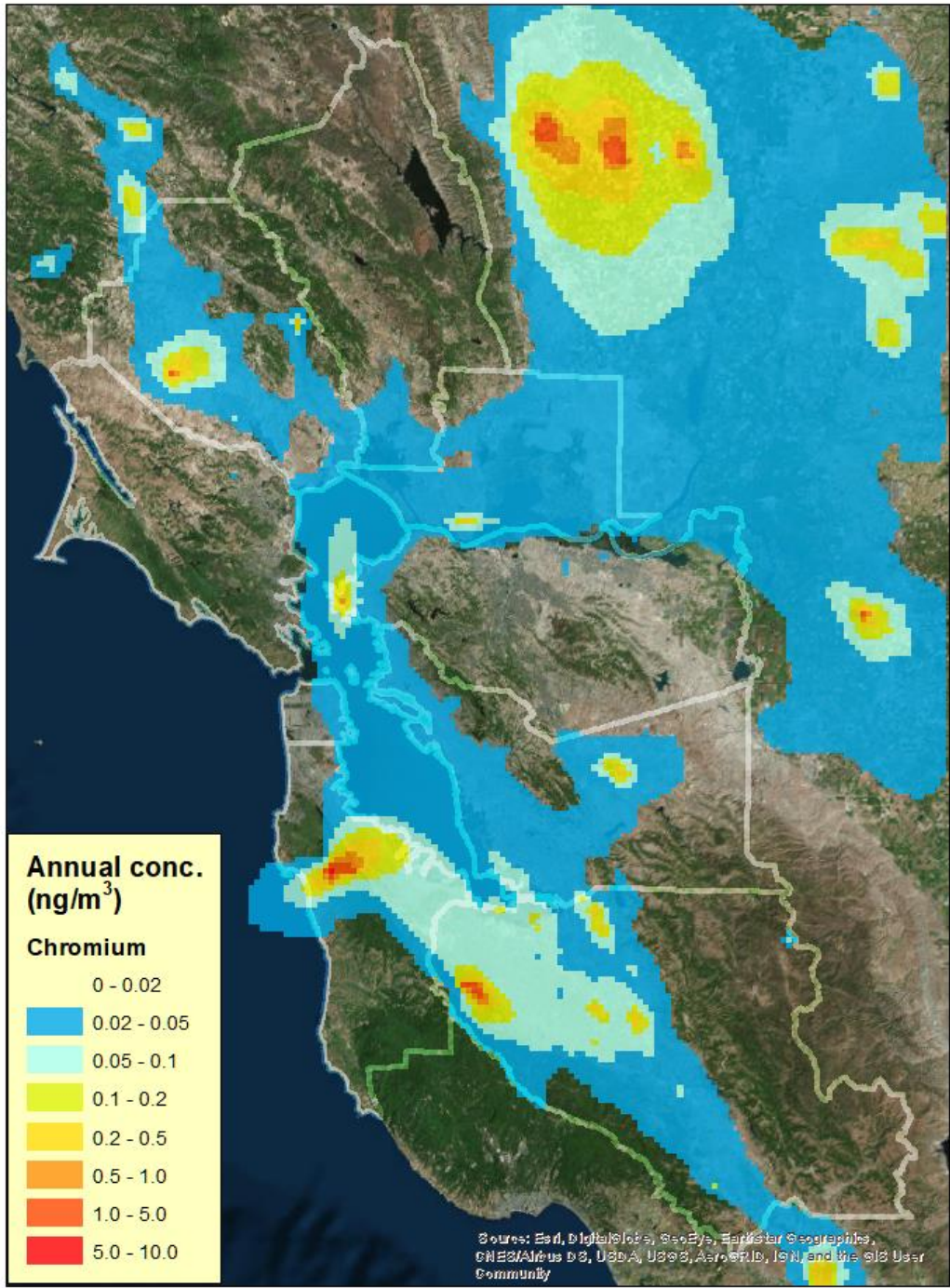
The highest annual average concentration of hexavalent chromium is simulated to occur east of Half Moon Bay ($8.3 \text{ ng}/\text{m}^3$). Concentrations above $1 \text{ ng}/\text{m}^3$ are seen northwest of Petaluma and west of Cupertino. Each of these areas are associated with mineral processing activities in the NATA area source inventory. Outside of the Bay Area, the Stockton and Sacramento areas also show above $1 \text{ ng}/\text{m}^3$ concentrations.

The simulated annual average cadmium concentration peaks at Lathrop ($0.9 \text{ ng}/\text{m}^3$). Simulated concentrations are below $0.05 \text{ ng}/\text{m}^3$ in the Bay Area except for Islais Creek Channel ($0.06 \text{ ng}/\text{m}^3$).

Simulated hot spots for lead are located at local airports such as Reid-Hillview Airport ($39.0 \text{ ng}/\text{m}^3$), Palo Alto Airport ($37.0 \text{ ng}/\text{m}^3$), Livermore Municipal Airport ($33.9 \text{ ng}/\text{m}^3$), Watsonville Municipal Airport ($28.2 \text{ ng}/\text{m}^3$), San Carlos Airport ($25.2 \text{ ng}/\text{m}^3$), Hayward Executive Airport ($23.6 \text{ ng}/\text{m}^3$), Nut Tree Airport ($23.1 \text{ ng}/\text{m}^3$) and Buchanan Field Airport ($22.9 \text{ ng}/\text{m}^3$). Lead concentrations quickly diminish as distance from the source increases.

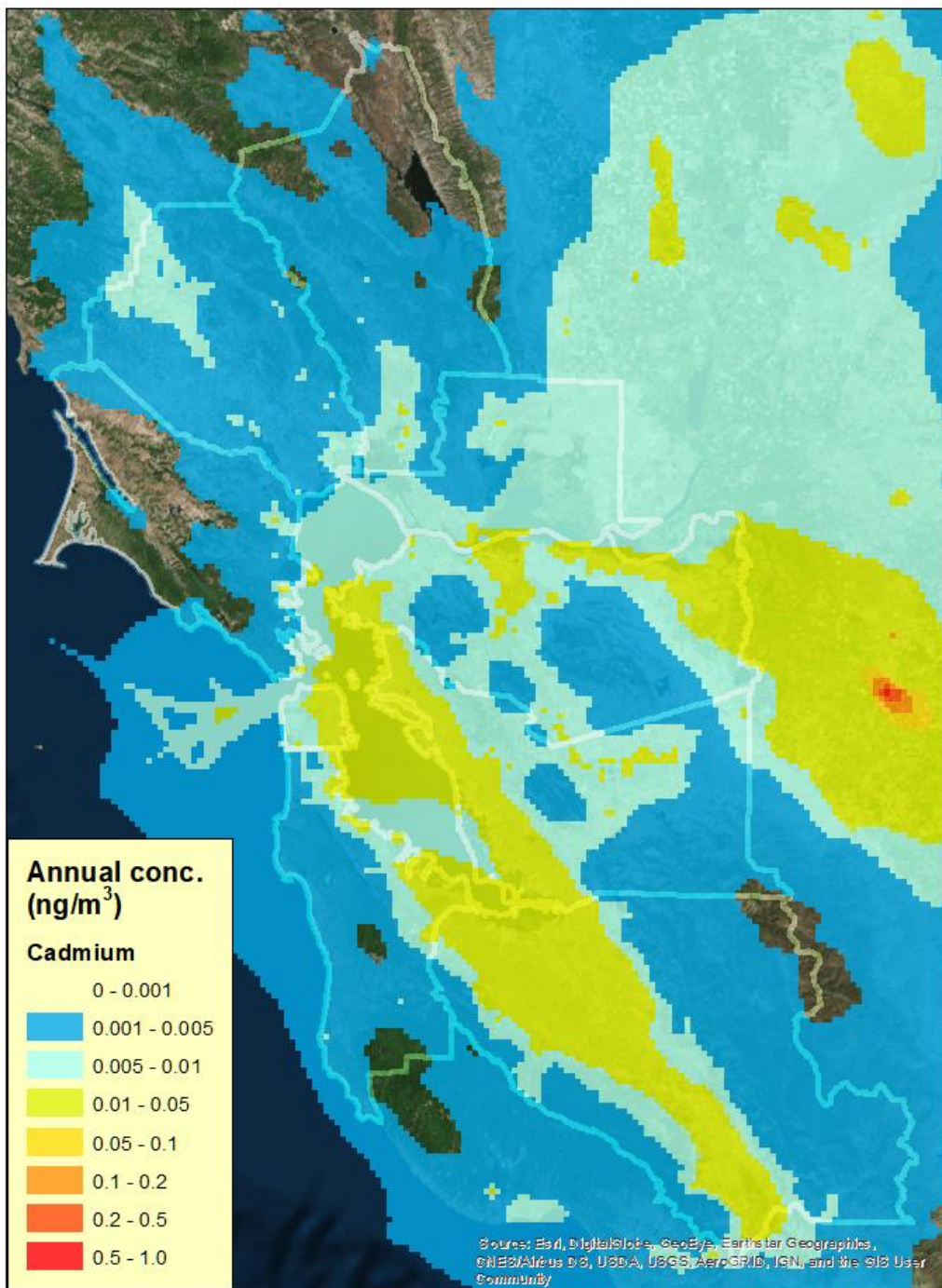
The simulated annual average nickel concentration is highest at Lathrop ($31.5 \text{ ng}/\text{m}^3$). The second highest is at Benicia near the Valero Refinery ($17.9 \text{ ng}/\text{m}^3$). Other hot spots in the Bay Area are Livermore ($7.8 \text{ ng}/\text{m}^3$), Richmond ($6.1 \text{ ng}/\text{m}^3$) and west of Cupertino ($5.4 \text{ ng}/\text{m}^3$).

The highest annual average mercury concentration of $1.8 \text{ ng}/\text{m}^3$ is simulated to occur just west of Cupertino, with the surrounding areas showing above $0.5 \text{ ng}/\text{m}^3$. Simulated concentrations are below $0.5 \text{ ng}/\text{m}^3$ for all other areas except for Rodeo which shows $0.6 \text{ ng}/\text{m}^3$.



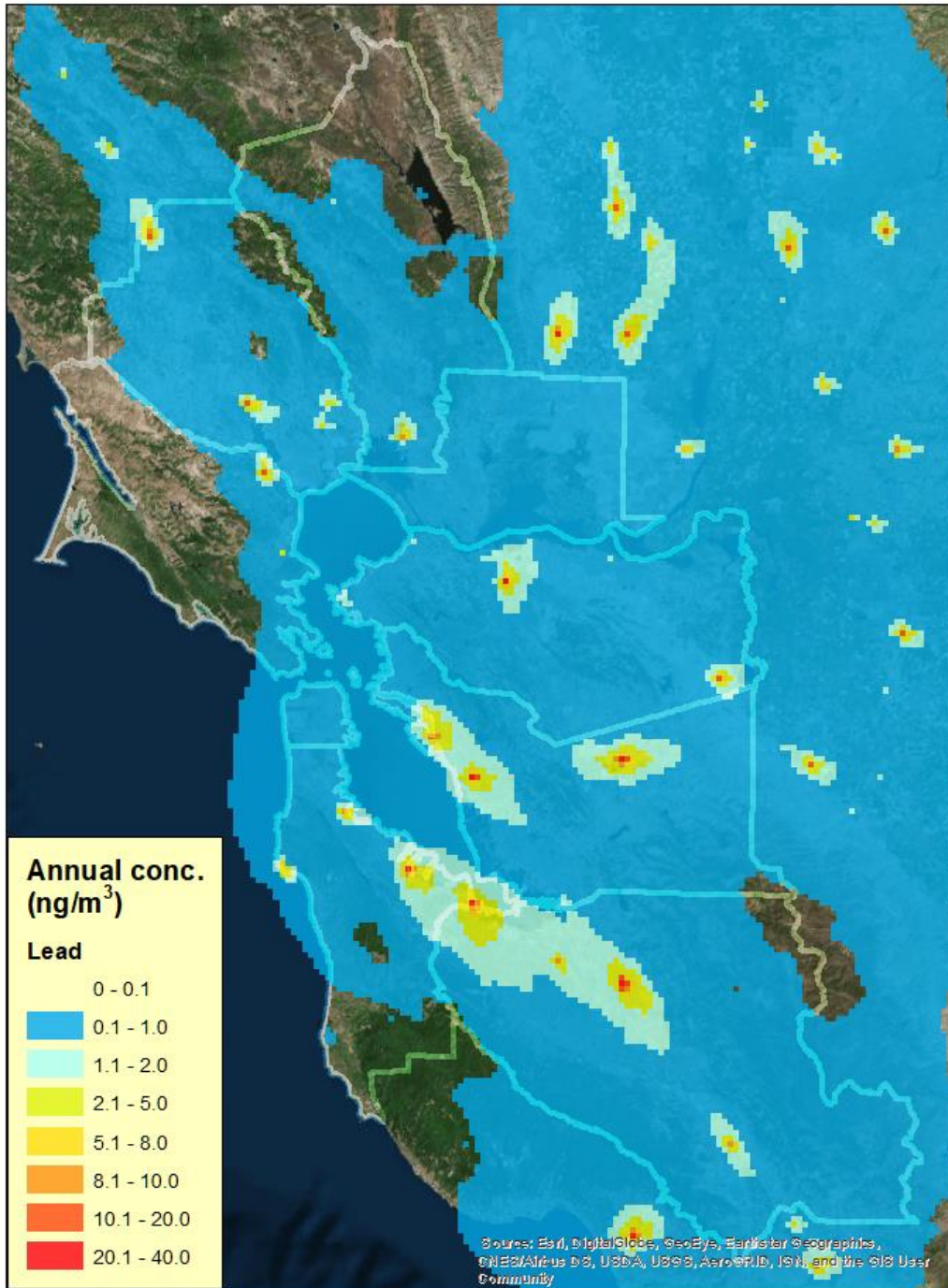
Maximum: 8.3

Figure C1: Simulated annual average hexavalent chromium concentrations for 2016.



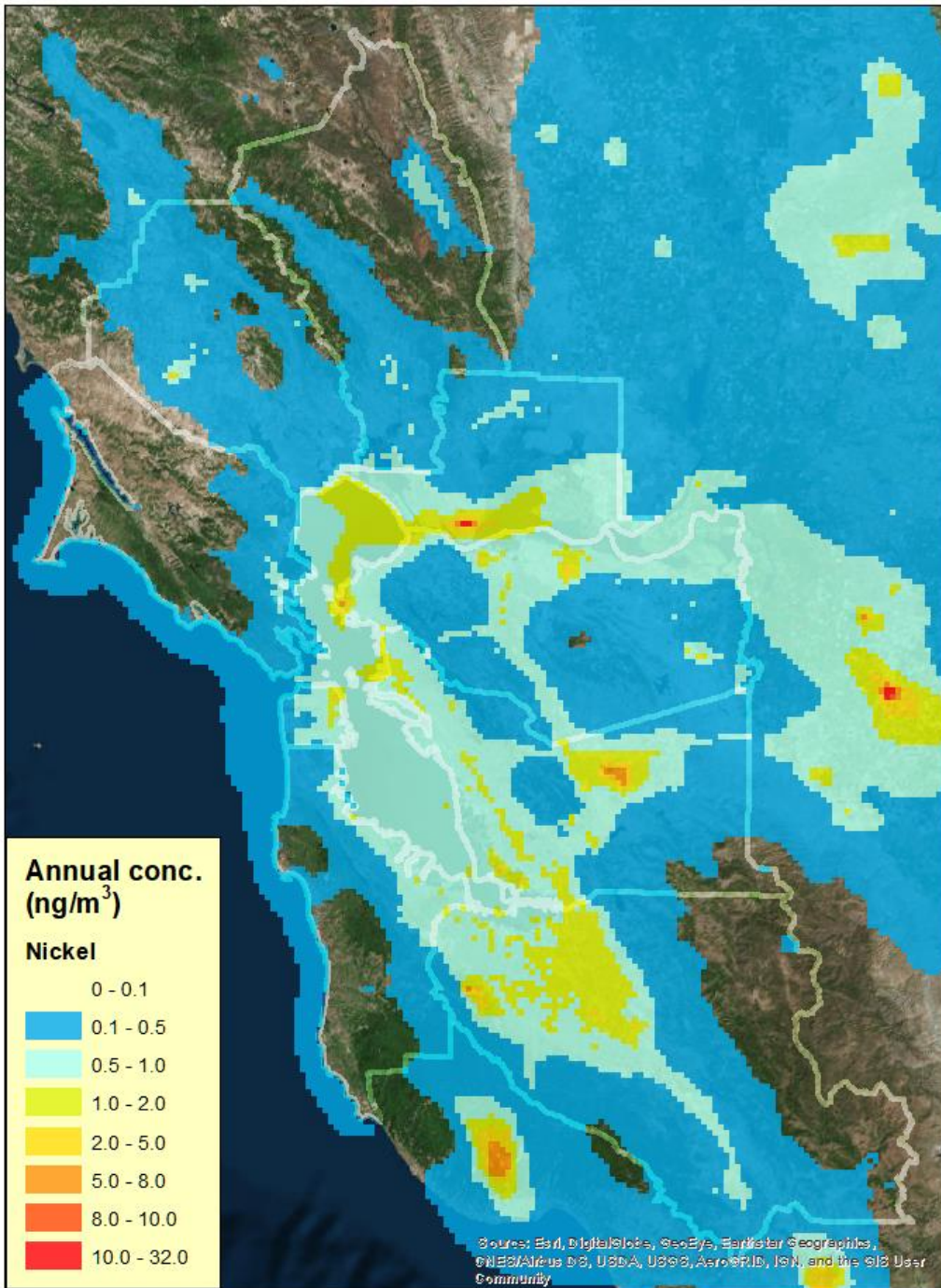
Maximum: 0.9

Figure C2: Simulated annual average cadmium concentrations for 2016.



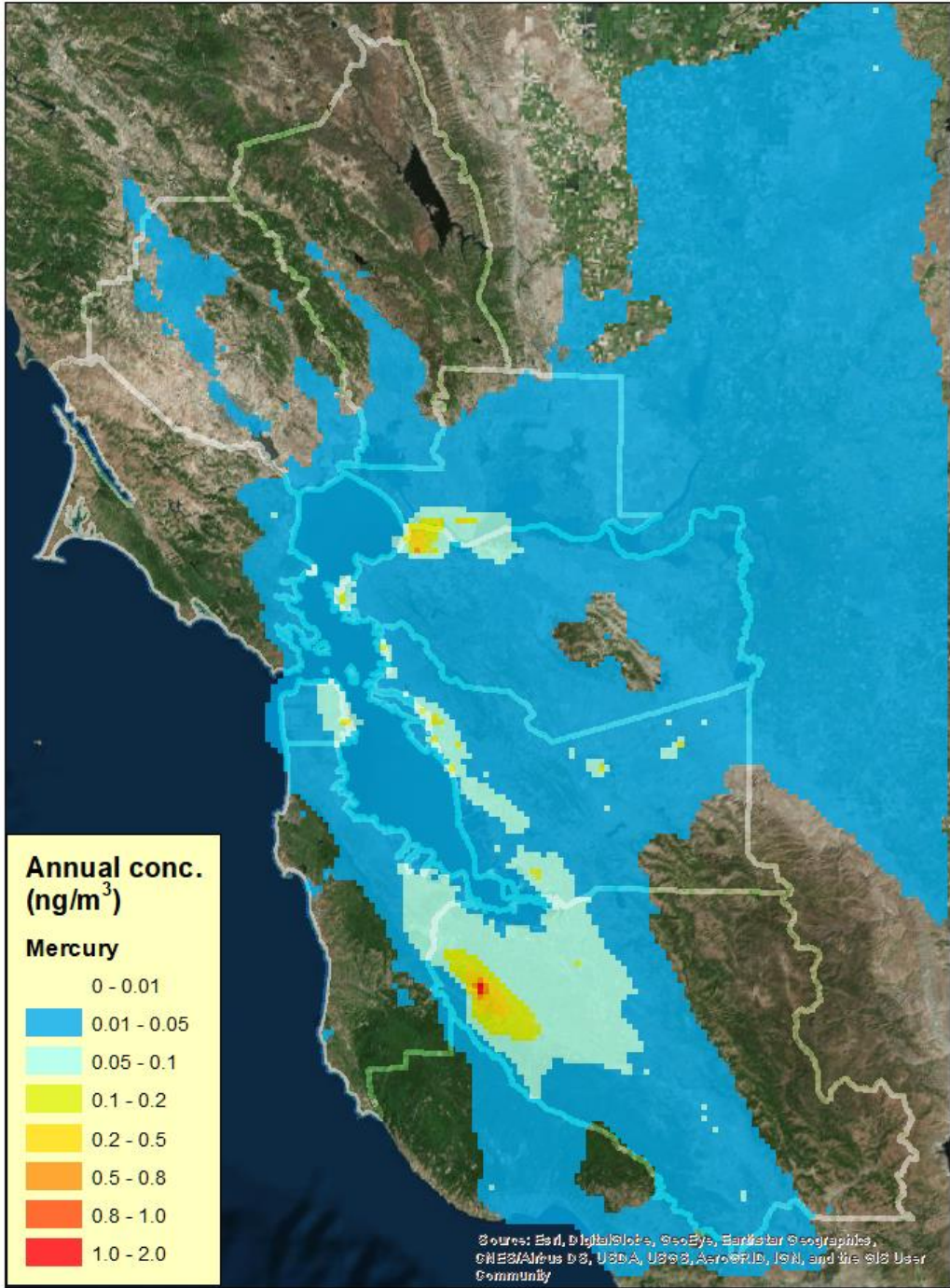
Maximum: 39.0

Figure C3: Simulated annual average lead concentrations for 2016.



Maximum: 31.5

Figure C4: Simulated annual average nickel concentrations for 2016.



Maximum: 1.8

Figure C5: Simulated annual average mercury concentrations for 2016.

Appendix D: Excess Cancer Risk in West Oakland

As mentioned in Section 3, in addition to the base case, a “control case” simulation was conducted with all anthropogenic emissions from the West Oakland source domain removed, which provides regional background contributions to air toxics in the West Oakland. The differences between the base and control cases represent contributions from the local anthropogenic sources in West Oakland.

Figures D1 through D4 present the base case annual average concentrations of the air toxics and show significant mass concentrations in the West Oakland receptor domain (formaldehyde, acetaldehyde, benzene, and diesel PM). Annual average formaldehyde concentrations range from 1.3 to 5.1 $\mu\text{g}/\text{m}^3$. The northwestern section of the West Oakland community (the community border is indicated by the red line in the figure) shows the highest concentration.

The highest annual average acetaldehyde concentration (0.83 $\mu\text{g}/\text{m}^3$) within the West Oakland receptor domain is located outside of the West Oakland community, at a grid cell in the northwestern corner of the receptor domain. The concentration gradient of acetaldehyde is not as dramatic as that of formaldehyde. The highest acetaldehyde concentration in the West Oakland community is 0.75 $\mu\text{g}/\text{m}^3$.

The annual average benzene concentration is highest (0.68 $\mu\text{g}/\text{m}^3$) at the northeastern corner of the West Oakland receptor domain. Within the West Oakland community border, the concentration ranges from 0.4 to 0.6 $\mu\text{g}/\text{m}^3$ except for the small area in the northeastern corner of the community.

The annual average diesel PM concentrations peak at the northwestern corner of the receptor domain (1.3 $\mu\text{g}/\text{m}^3$), suggesting significant contributions from diesel traffic over the Bay Bridge. Within the West Oakland community, the concentration remains below 0.9 $\mu\text{g}/\text{m}^3$.

Figure D5 shows relative fractions of individual air toxics mass concentrations averaged over the 5x4 grid cells within the West Oakland receptor domain. Formaldehyde accounts for almost half of the total air toxic concentration. The next highest is diesel PM, which makes up 19% of the total mass concentration, followed by acetaldehyde (17%) and benzene (13%). The combined toxic metals contribute less than 0.1%.

Figure D6 shows expected excess cancer incidences per million people for the base case, which was calculated as described in Section 4, combining impacts from all the air toxics. The spatial pattern of the cancer risk is similar to that of diesel PM concentrations, with the highest number of excess cancer incidences (1069 per million) occurring at the northwestern corner of the receptor domain, and the lowest (496 per million) occurring at the grid cell that partially overlaps the southwestern tip of the West Oakland community. This is expected, as more than 80% of the combined cancer risk is attributed to diesel PM (see Figure D7). Although formaldehyde is the largest contributor in terms of mass concentration in the area, excess cancer risk is dominated by diesel PM due to its high risk factor.

Figure D8 shows the same plot as Figure D6, but for the control case. The spatial gradient of the excess cancer risk somewhat decreased compared to Figure D6, but the northwestern corner grid cell still shows the highest value, indicating the importance of non-local contributions from the Bay Bridge.

Figure D9 shows the differences in the excess cancer risk between the base and control cases. The Chinatown area (the southeastern corner of the West Oakland receptor domain) would benefit the most (485 cancer incidences per million avoided) from eliminating all anthropogenic emissions in the West Oakland source domain. Similarly, significant benefit is expected at the northwestern corner of the receptor domain, although the population in this grid cell is very small. Within the West Oakland community, the cancer incidences avoided range from 174 to 365 per million.

Figure D10 is the same as Figure D9 except the relative contributions of local vs. background toxics to excess cancer risks is shown on a percentage basis. Local sources account for about 50% of cancer risk in the China Town area, and about 40% in the West Oakland community. The lowest local source contribution to cancer risk is about 27% and is located at a cell in the southwestern corner of the domain.

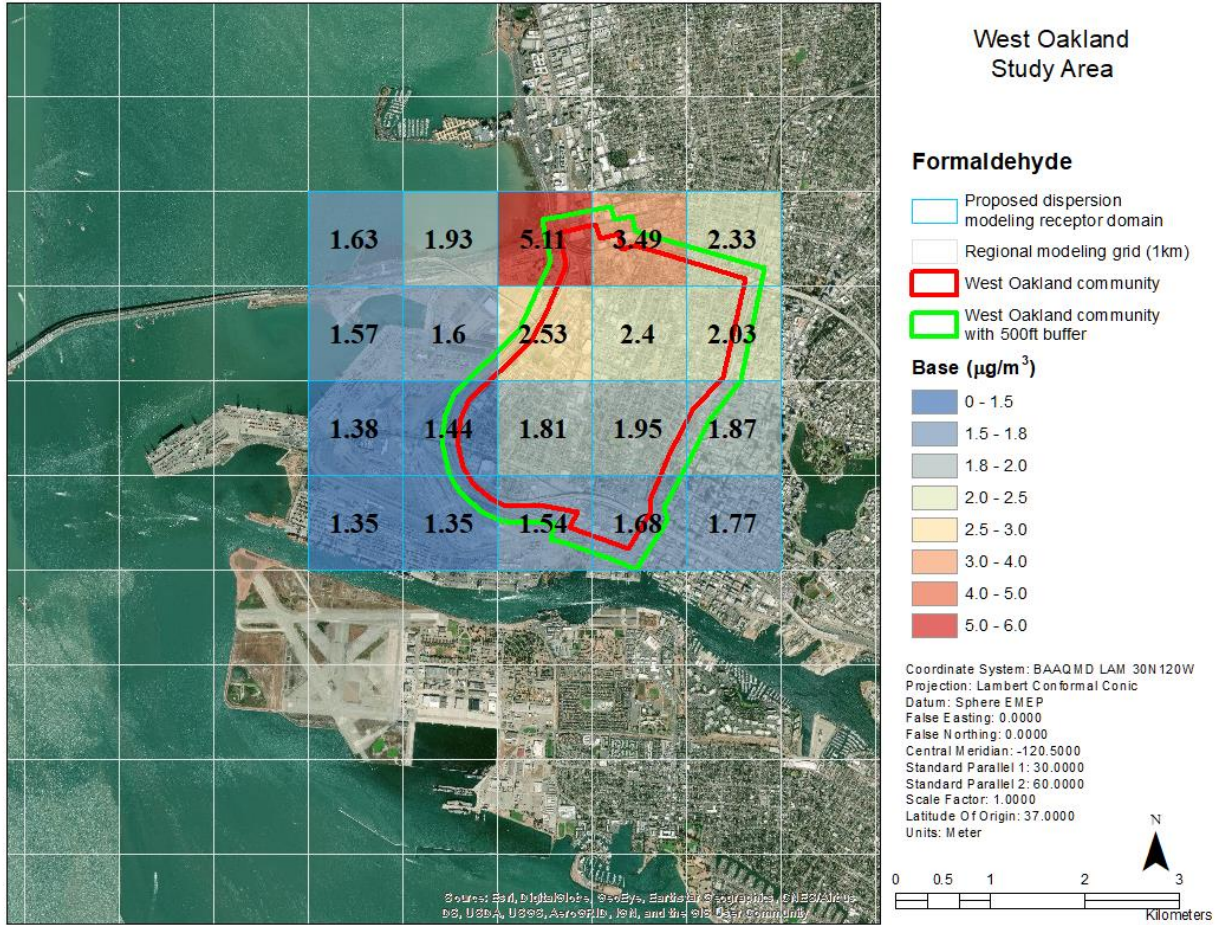


Figure D1: Annual average concentrations of formaldehyde in the West Oakland receptor domain for the base case.

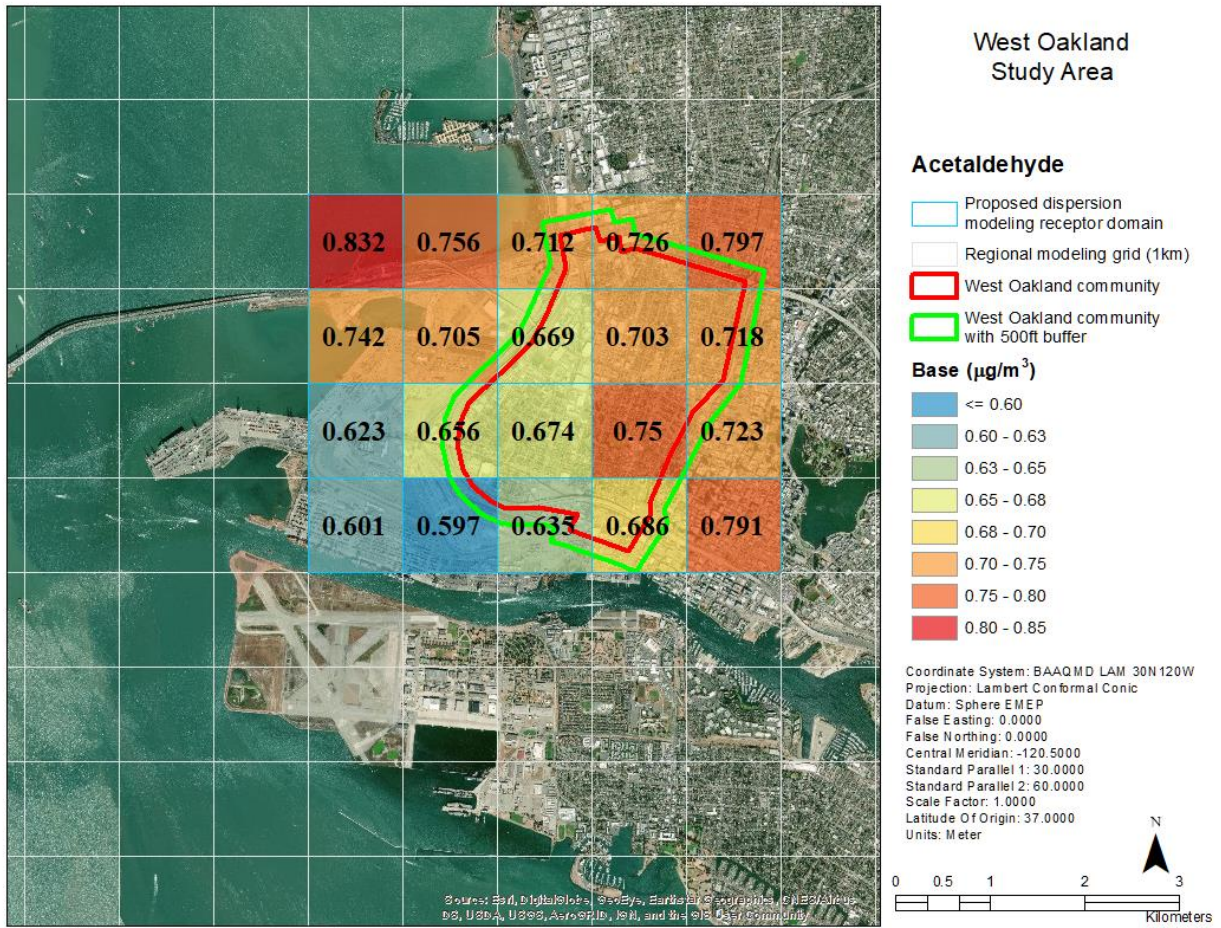


Figure D2: Annual average concentrations of acetaldehyde in the West Oakland receptor domain for the base case.

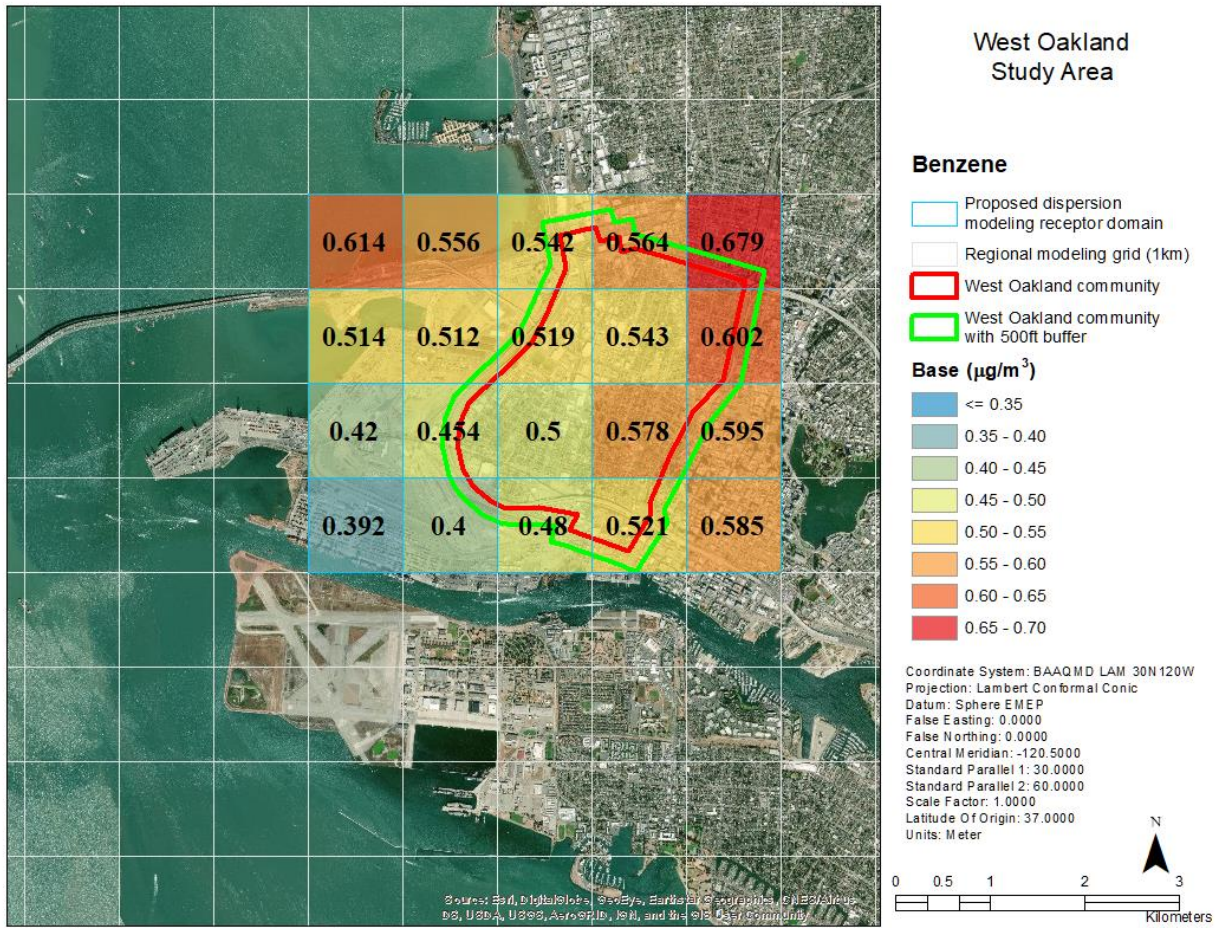


Figure D3: Annual average concentrations of benzene in the West Oakland receptor domain for the base case.

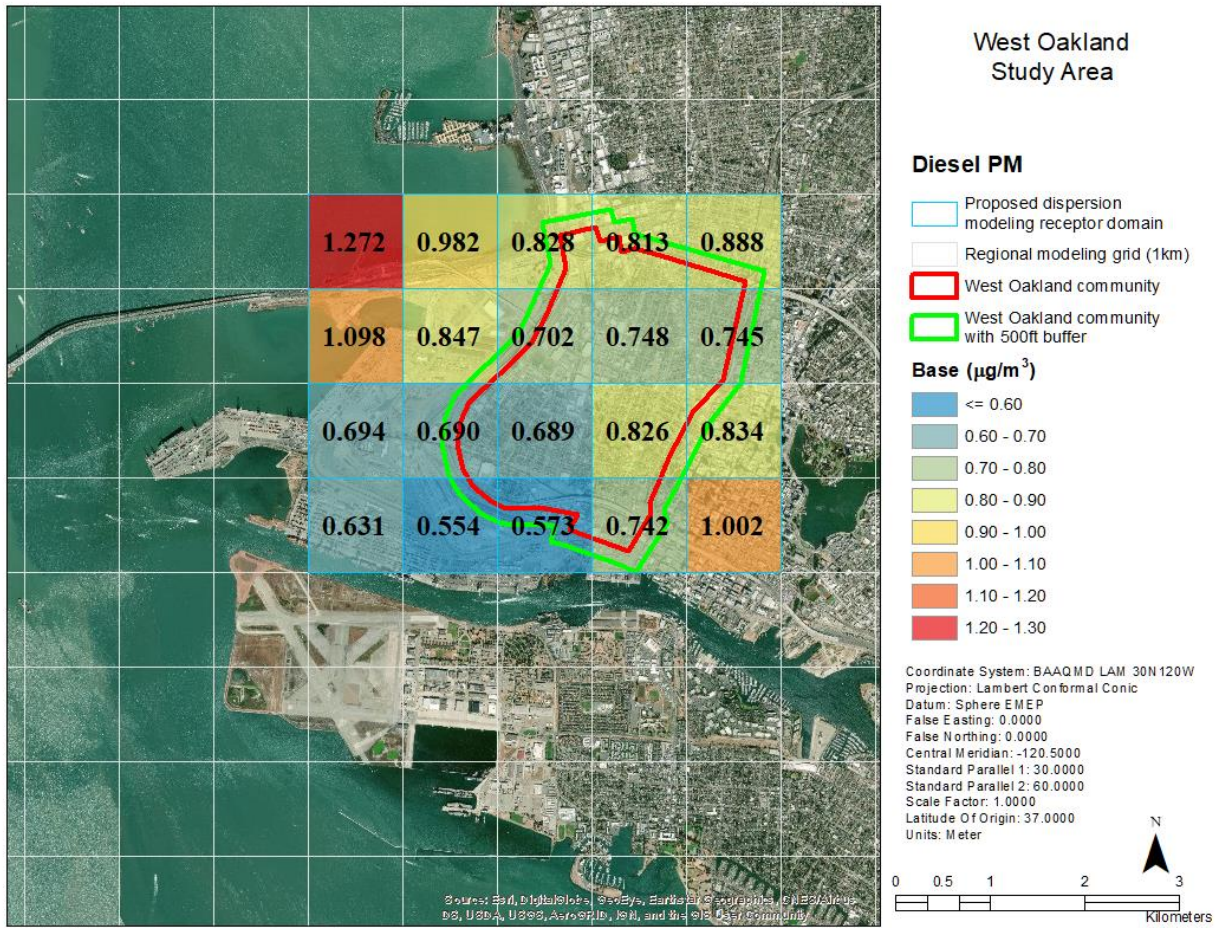


Figure D4: Annual average concentrations of diesel PM in the West Oakland receptor domain for the base case.

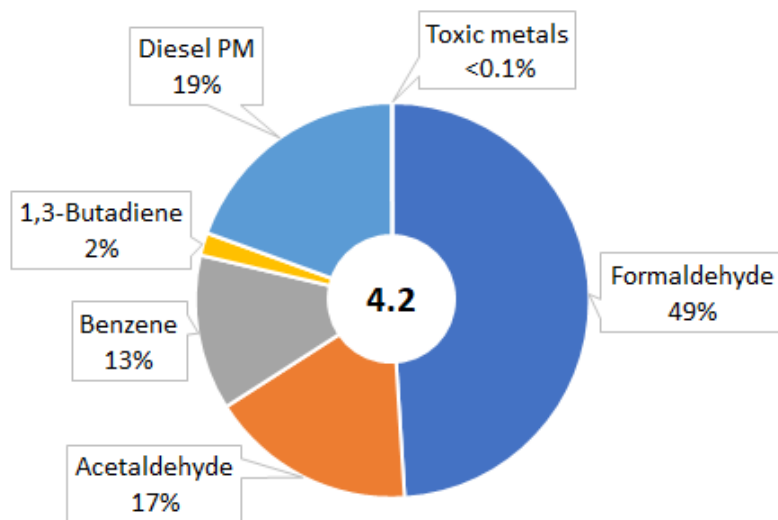


Figure D5: Relative contributions of individual air toxics to total air toxics mass concentration in West Oakland. The number in the center represents the combined annual average concentration ($\mu\text{g}/\text{m}^3$) of all air toxics modeled, averaged over the 5x4 grid cells within the West Oakland receptor domain.

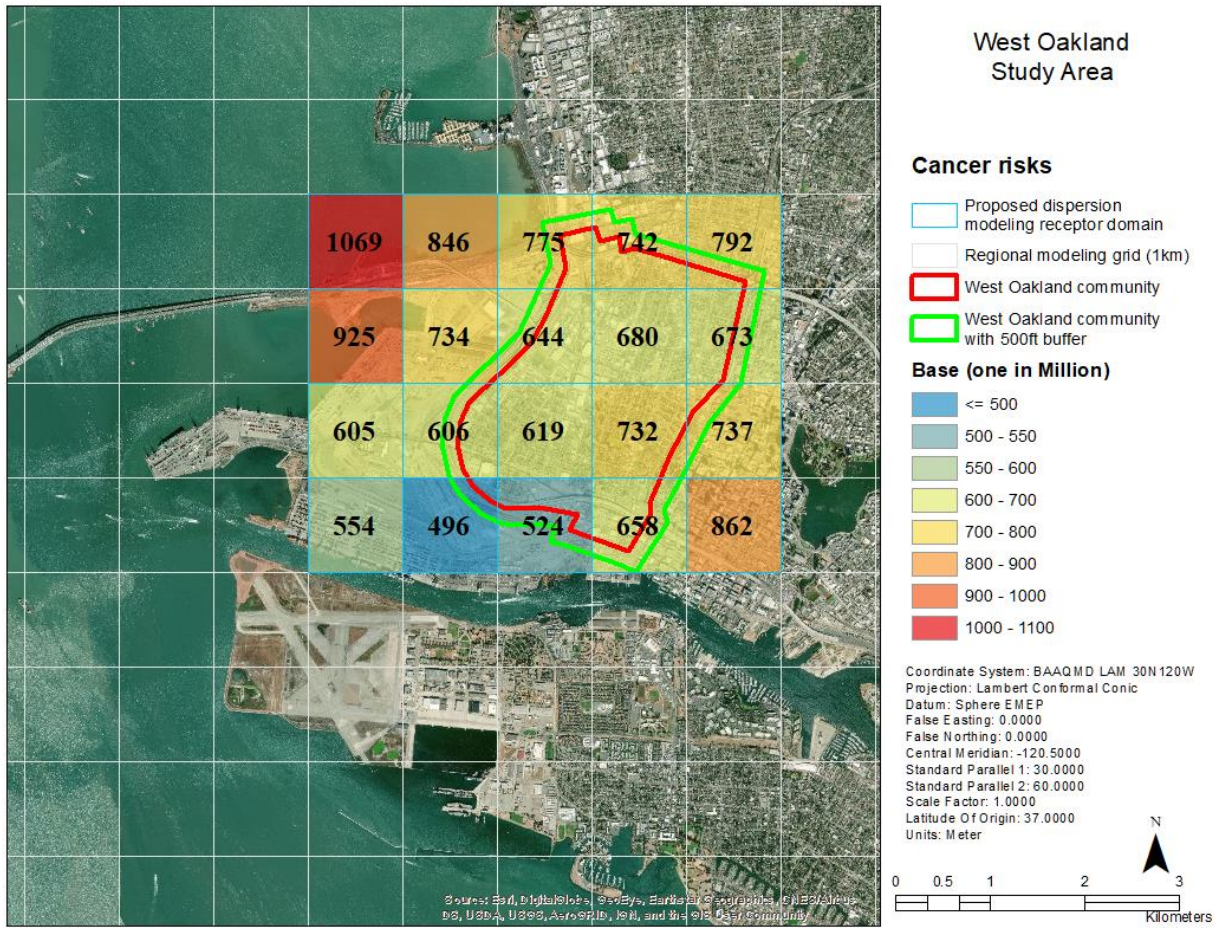


Figure D6: Expected excess cancer incidences per million in the West Oakland receptor domain (base case).

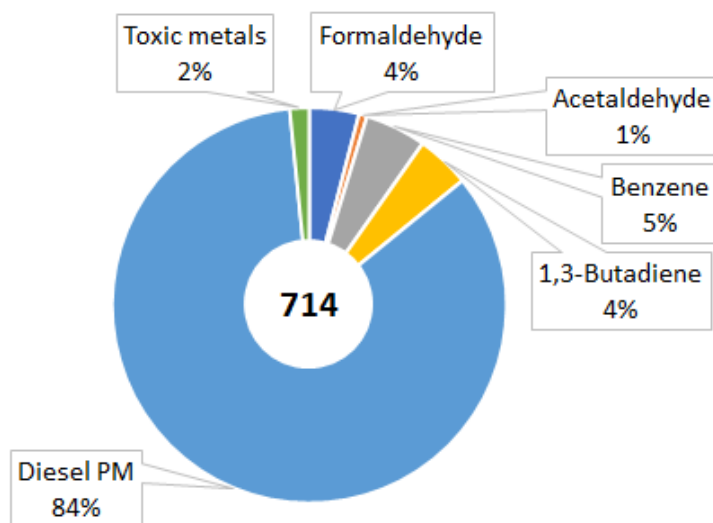


Figure D7: Relative contributions of individual air toxics to total excess cancer risk in West Oakland. The number in the center represents the combined excess cancer incidences (per million people) due to all air toxics modeled, averaged over the 5x4 grid cells within the West Oakland receptor domain.

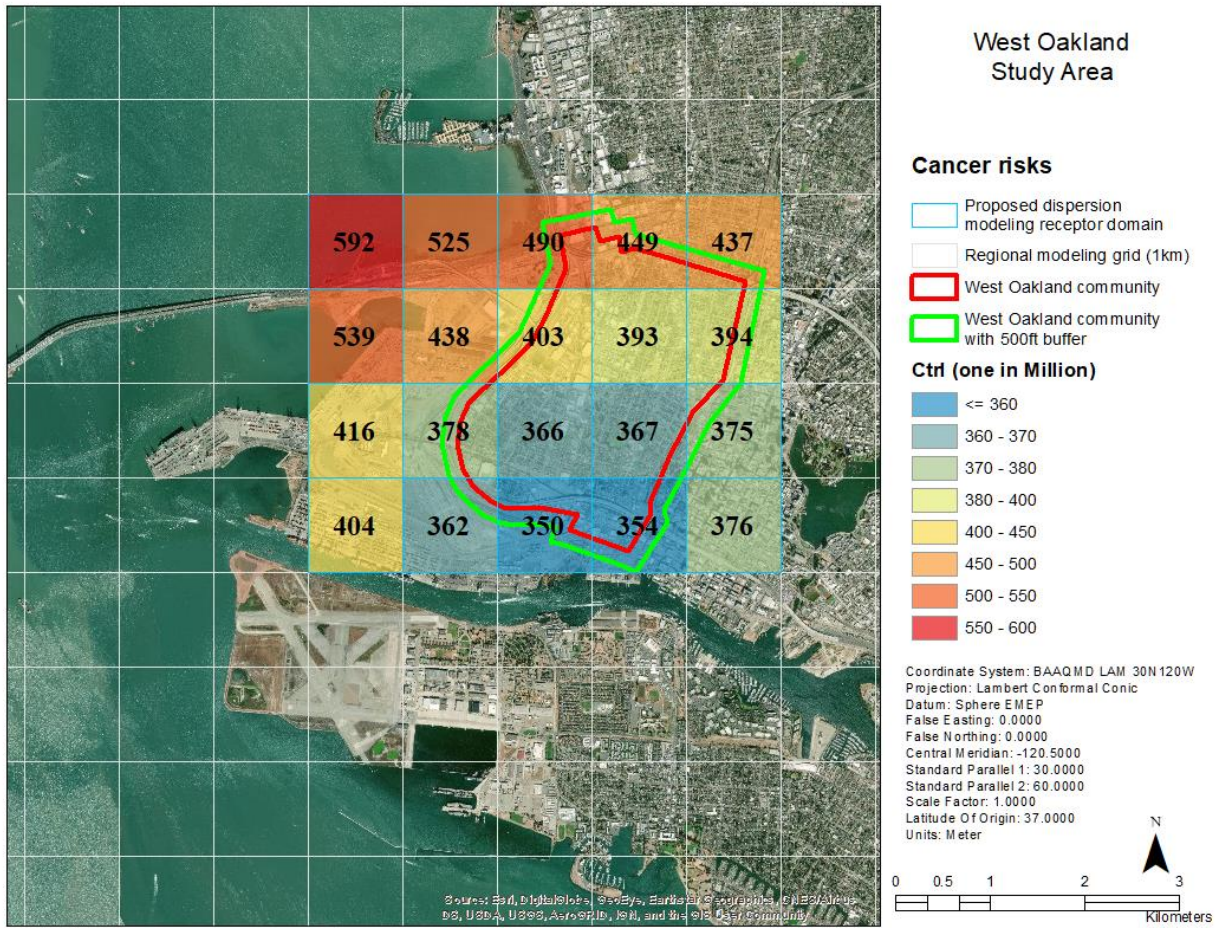


Figure D8: Expected excess cancer incidences per million in the West Oakland receptor domain (control case).

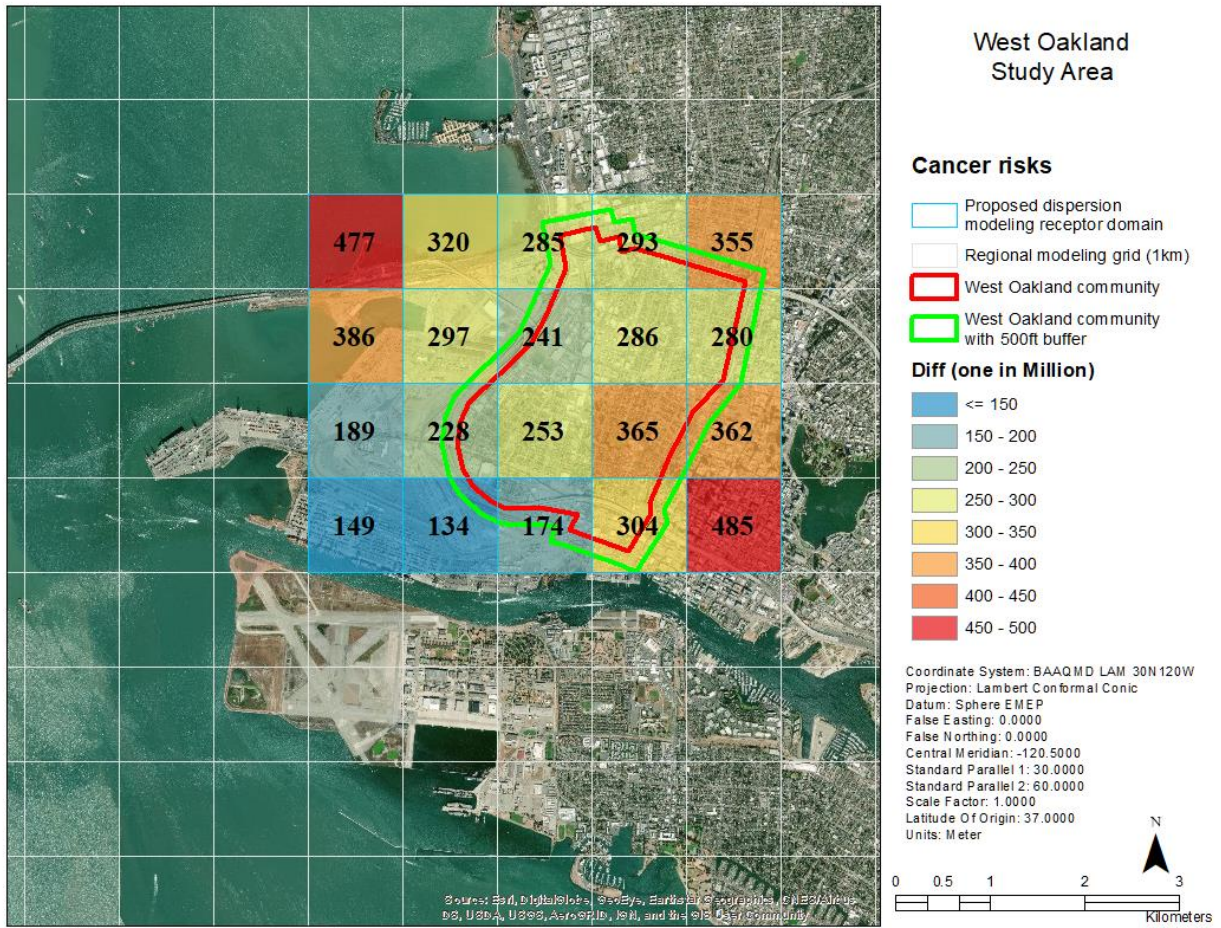


Figure D9: Differences in expected excess cancer incidences per million in the West Oakland receptor domain between the base and control cases.

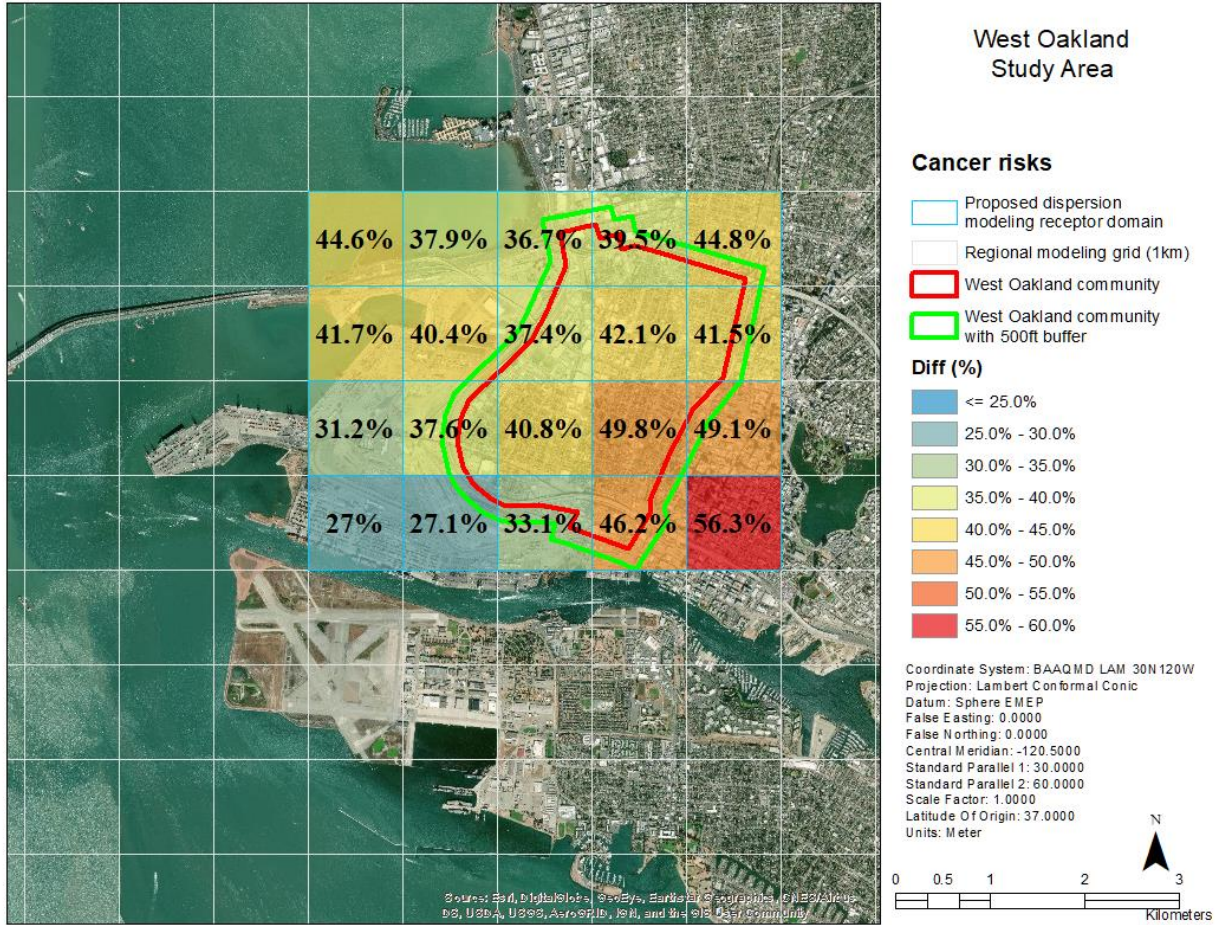


Figure D10: Percentage contribution of cancer risks due to the local anthropogenic emissions within West Oakland.