Appendix A.2:

Modeling Fine Particulate Matter Emissions from the Chevron Richmond Refinery: An Air Quality Health Impact Analysis (Version 2)

Version 2 promoted to final from interim draft.

Updates since version 1: Minor changes and corrections to footnotes in Tables ES1 and 4.1; added text to acknowledge adjustments to 2018 baseline emissions to reflect facility changes since 2018.

BAY AREA AIR QUALITY MANAGEMENT DISTRICT
375 Beale Street, San Francisco, CA 94105

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Modeling Fine Particulate Matter Emissions From the Chevron Richmond Refinery: An Air Quality Health Impact Analysis (Version 2)

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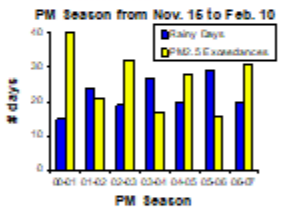

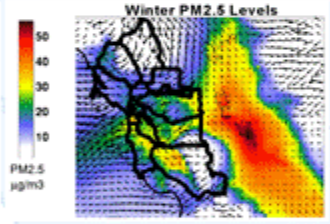

Prepared by:

Yuanyuan Fang, Statistician
Bonyoung Koo, Senior Atmospheric Modeler
Andrea Baird, Technical Editor
Yiqin Jia, Atmospheric Modeler
James Cordova, Air Quality Meteorologist
Jeff Matsuoka, Research Analyst
Stephen Reid, Senior Advanced Projects Advisor

Contributors:

David Holstius, Senior Advanced Projects Advisor
Saffet Tanrikulu, Air Quality Modeling and Analysis Manager

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Executive Summary

The Bay Area Air Quality Management District (District) has conducted modeling analyses to assess the air quality and health impacts of fine particulate matter ($PM_{2.5}$) emissions from the Chevron Refinery in Richmond, California. These analyses are part of a larger effort to estimate the impacts of $PM_{2.5}$ emissions from major industrial facilities in the Bay Area. This work will support the District's rule development efforts and community-scale assessments conducted under Assembly Bill 617 (AB 617), which established collaborative programs to reduce disparities in air pollution exposure across California.

The California Puff (CALPUFF) model was used for estimating ambient $PM_{2.5}$ concentrations from Chevon refinery emissions. CALPUFF was applied at two spatial scales: a 1-km grid covering the entire Bay Area and a 100-m grid covering a smaller study area. The model was run using emission estimates derived from a base-year 2018 inventory but with adjustments to reflect facility changes since 2018. (See Koo et al., 2021a, for a discussion of emissions adjustments.) Year-specific meteorological inputs for three years (2016–2018) were utilized to minimize the impact of year-to-year variations in meteorology on estimated $PM_{2.5}$ levels. Average results from the three annual simulations were used as inputs to the US Environmental Protection Agency's Benefits Mapping and Analysis Program – Community Edition (BenMAP–CE), which estimates health impacts associated with changes in ambient pollutant levels, as well as conventional valuations of those impacts (expressed in US dollars).

BenMAP–CE was applied for three scenarios at the Census block level across the 100-m grid that defined the study area. The baseline scenario assessed the impacts of $PM_{2.5}$ emitted from all modeled sources at the Chevron refinery. Scenarios A and B respectively assessed reductions in these impacts due to the achievement of PM_{10} limits under Control Scenario A (0.020 gr/dscf) and Control Scenario B (0.010 gr/dscf) at the refinery's fluidized catalytic cracking unit (FCCU).

As modeled, 5.1 to 11.6 premature deaths per year were attributed to baseline $PM_{2.5}$ emissions from the Chevron refinery. The conventional valuation of all the health impacts included in our assessment (including, but not limited to, those deaths) was 52.5 to 118 million US dollars per year. The implementation of controls to achieve Control Scenario A and Control Scenario B at the refinery's FCCU were estimated to reduce annual excess deaths by 13% and 23%, respectively, and resulted in benefits valued at 6.8 to 15.2 and 12.2 to 27.4 million dollars per year, respectively.

The valued benefits represent US EPA's national average valuation, and were not modified specifically for the Bay Area. Table ES.1 summarizes the health and monetary impacts of $PM_{2.5}$ from Chevron Richmond refinery emissions along with percent changes due to emissions controls.

Table ES.1: Summary of health and monetary impacts of $PM_{2.5}$ from Chevron Richmond refinery emissions and percent change of FCCU emissions under Control Scenario A and Control Scenario B.

Baseline Health Impact[1] of Chevron Richmond Refinery (Annual)		Valuation[2] (Annual)	Reduction under Control Scenario A	Reduction under Control Scenario B
Cardiovascular	0.5–4.3 heart attacks	$63 k–$600 k	−13%	−22%
	1.0 hospital admissions	$47 k	−13%	−22%
Restricted Activity	4,800 days	$360 k	−12%	−21%
Lost Work	820 days	$190 k	−12%	−21%
Asthma	200 exacerbations[3]	$12 k	−12%	−21%
	4 emergency room visits	$2 k	−12%	−21%
	0.1 hospital admissions	$1 k	−12%	−20%
Respiratory Illness[4]	140 upper tract[3]	$5 k	−12%	−20%
	100 lower tract[3]	$2 k	−12%	−20%
	8 bronchitis[3]	$4 k	−12%	−20%
	0.2 chronic lung disease	$5 k	−12%	−21%
Mortality[5]	5.1–11.6 premature deaths	$52.5 M–$118 M	−13%	−23%
			$6.8 M/yr to $15.2 M/yr	**$12.2 M/yr to $27.4 M/yr**

[1] On the study population (about 1 million people)
[2] Conventional US EPA valuations, in 2015 US dollars
[3] Subset of pediatric (≤ 18 years)
[4] Other than asthma
[5] Including infant mortality
k, thousand; M, million.

List of Acronyms

AB 617	Assembly Bill 617
BAAQMD	Bay Area Air Quality Management District
BenMAP–CE	Benefits Mapping and Analysis Program – Community Edition
CALPUFF	California Puff (model)
CDC	Center for Disease Control
ESP	Electrostatic Precipitator
EPA	Environmental Protection Agency
FCCU	Fluidized Catalytic Cracking Unit
$PM_{2.5}$	Particulate Matter 2.5 micrometers or less in diameter
WGS	Wet Gas Scrubber

Modeling Fine Particulate Matter Emissions From the Chevron Richmond Refinery: An Air Quality Health Impact Analysis (Version 2)

Introduction

The adoption of Assembly Bill 617 (AB 617) 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 (CARB), other state agencies, local air districts, community groups, community members, environmental organizations, regulated industries, and other key stakeholders to reduce harmful air pollutants in Bay Area communities.

As part of these programs, Air Quality Modeling and Analysis Section staff have been estimating concentrations of directly emitted fine particulate matter ($PM_{2.5}$) from major industrial facilities in the Bay Area. This information is being used to estimate the contributions of emitted $PM_{2.5}$ to ambient levels, assess the adverse impacts of those contributions on human health and welfare, and quantify the benefits of reducing those impacts through emission controls.

Atmospheric $PM_{2.5}$ is a complex mixture of suspended particles and liquid droplets having aerodynamic diameters of 2.5 μm or less. These particles are small enough to be inhaled into the lungs and thereby enter the bloodstream. Numerous studies have reported that $PM_{2.5}$ is deleterious to the respiratory and cardiovascular systems. In the lungs, $PM_{2.5}$ aggravates asthma, bronchitis, and other respiratory problems, leading to increased hospital admissions. In the heart and vascular system, $PM_{2.5}$ is associated with chronic hardening of the arteries (atherosclerosis) and triggering of heart attacks (acute myocardial infarctions). Decreased life expectancy, potentially on the order of years, has been documented.

The United States Environmental Protection Agency (US EPA) has developed the Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP–CE) to estimate and quantify conventional valuations of health impacts associated with changes in ambient pollutant levels (US EPA, 2018). Staff of the Air Quality Modeling and Analysis Section have been applying this program to estimate adverse impacts of $PM_{2.5}$ on Bay Area residents (Tanrikulu, et al., 2011). This program is also being used to assess the impacts of $PM_{2.5}$ emitted from major industrial facilities in the Bay Area.

The impacts of $PM_{2.5}$ from Chevron Richmond refinery emissions were analyzed for this report. The impacts of emissions from other major facilities will be reported separately.

Materials and methods

2.1 US EPA's BenMAP–CE computer program

In this study, BenMAP–Community Edition (BenMAP–CE), version 1.5, was used (https://www.epa.gov/benmap). This program was designed to estimate changes in human health due to changes in ambient air quality for specific populations and to estimate conventional valuations of these impacts (in US dollars).

The valuation process takes into account both the direct costs of illnesses such as actual medical costs and lost worker hours and indirect costs reflecting *willingness to pay* to avoid pain and suffering as well as premature death. The direct costs alone may substantially underestimate the total valuation assigned to reductions in these outcomes. For pollutants capable of causing death, such as $PM_{2.5}$, the mortality-based component tends to far outweigh the morbidity-based component. The calculations implemented by BenMAP–CE include assessing the change in population exposure, using health impact functions to estimate the incremental change in selected human health outcomes based on the exposure difference, and evaluating the range of monetary valuations associated with these outcomes.

Epidemiological data are used to develop concentration–response functions, which BenMAP–CE uses to quantify the linkages between pollutant exposures and adverse health outcomes. These functions are typically stratified by population subgroups (e.g., age groups) and account for the effects associated with a specific duration and degree of pollutant exposure. Population data and pollutant concentration data input to BenMAP–CE must be prepared in a manner consistent with these concentration–response functions. Epidemiological data linking $PM_{2.5}$ exposure and mortality are typically stratified by age group (e.g., infants, 18 years of age and older, etc.) and reflect an annual averaging period.

The BenMAP–CE program overlays population data onto changes in ambient pollutant concentrations to calculate spatially resolved impacts associated with pollutant exposure. Pollutant concentration data are taken from air quality model simulations or observations.

The study described in this report was the first of its kind to use high-resolution simulated pollutant fields to evaluate $PM_{2.5}$ health impacts over the Bay Area. High-resolution simulations reproduced the sharp spatial gradients in pollutant concentrations that result in significant neighborhood-to-neighborhood differences in human exposures.

An alternative approach would be to use air monitoring data. This approach would require interpolating pollutant levels from a network of monitors to construct levels over unmonitored neighborhoods. Since air monitoring data include concentrations from emissions of all sources, this approach is not applicable to our project that assesses health impacts of emissions from a specific source or proposed or adopted emissions control.

Applications of BenMAP–CE require the development of two sets of inputs: ambient $PM_{2.5}$ concentrations and population data. The preparation of these datasets for this study is discussed below.

2.2 Preparation of $PM_{2.5}$ concentrations

The California Puff (CALPUFF) model was used for estimating ambient $PM_{2.5}$ concentrations from Chevron Richmond refinery emissions (Koo et al., 2021a) and from PBF Martinez refinery emissions (Koo et al., 2021b). CALPUFF estimates pollutant concentrations at predefined receptor locations. Two receptor domains were established for the simulations. One covered the entire Bay Area at 1-km grid resolution, and the other covered a smaller area at 100-m grid resolution.

Results from the larger domain encompassing emissions from both Chevron Richmond and the PBF Martinez refineries were used to establish a "study area" approximating a "refinery corridor." This study area, consisting of the union of Census blocks for which an average modeled contribution (from both facilities combined) was determined to meet or exceed 0.1 $\mu g/m^3$ $PM_{2.5}$, was used to scope the residential population for which impacts were assessed.

CALPUFF was applied for three years (2016, 2017, and 2018) using year-specific meteorology and the same base-year (2018) emission estimates that included all inventoried $PM_{2.5}$ emissions from the refineries. The average results from the three annual simulations were used for health impacts analyses to minimize the effects of year-to-year variability in meteorology on ambient $PM_{2.5}$ levels. The average concentrations from the baseline simulation of the Chevron Richmond refinery are shown in Figure 2.1.

CALPUFF was also applied for two additional simulations for the same years and the resulting concentrations were averaged in the same manner as described above: (1) a simulation with emissions only from the refinery's fluidized catalytic cracking unit (FCCU) and (2) a simulation with emissions only from the refinery's FCCU controlled with an assumed wet gas scrubber (WGS). Air District staff believes that the more stringent 0.010 gr/dscf standard under Control Scenario B could only be met with a wet gas scrubber.

Analyses were also conducted for an assumed emissions rate corresponding to the 0.020 gr/dscf standard under Control Scenario A. Air District staff assumes stack release parameters would remain consistent with the current refinery configuration. For this scenario, concentrations estimated with the FCCU emissions only was uniformly reduced 33%, and the resulting concentrations were subtracted from the base simulation. This percent reduction is consistent with the 0.020 gr/dscf standard. Figure 2.2a shows reductions in $PM_{2.5}$ concentrations due to the 0.020 gr/dscf standard (scenario A). Figure 2.2b shows reductions in $PM_{2.5}$ concentrations due to the 0.010 gr/dscf standard (assuming WGS control) from the Chevron Richmond refinery (scenario B).

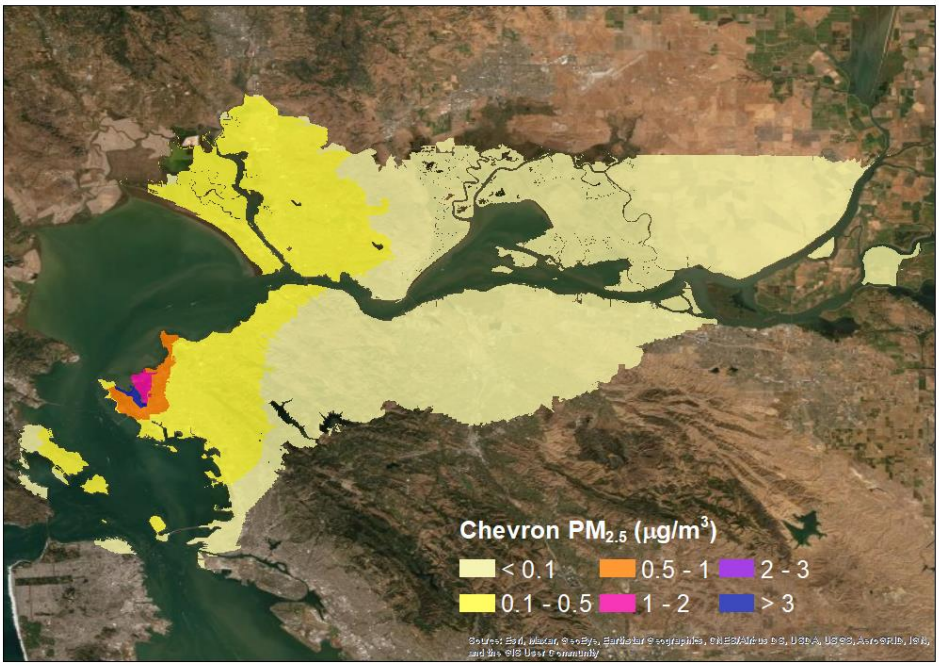

Figure 2.1: Average $PM_{2.5}$ concentrations from the baseline scenario for the Chevron Richmond refinery.

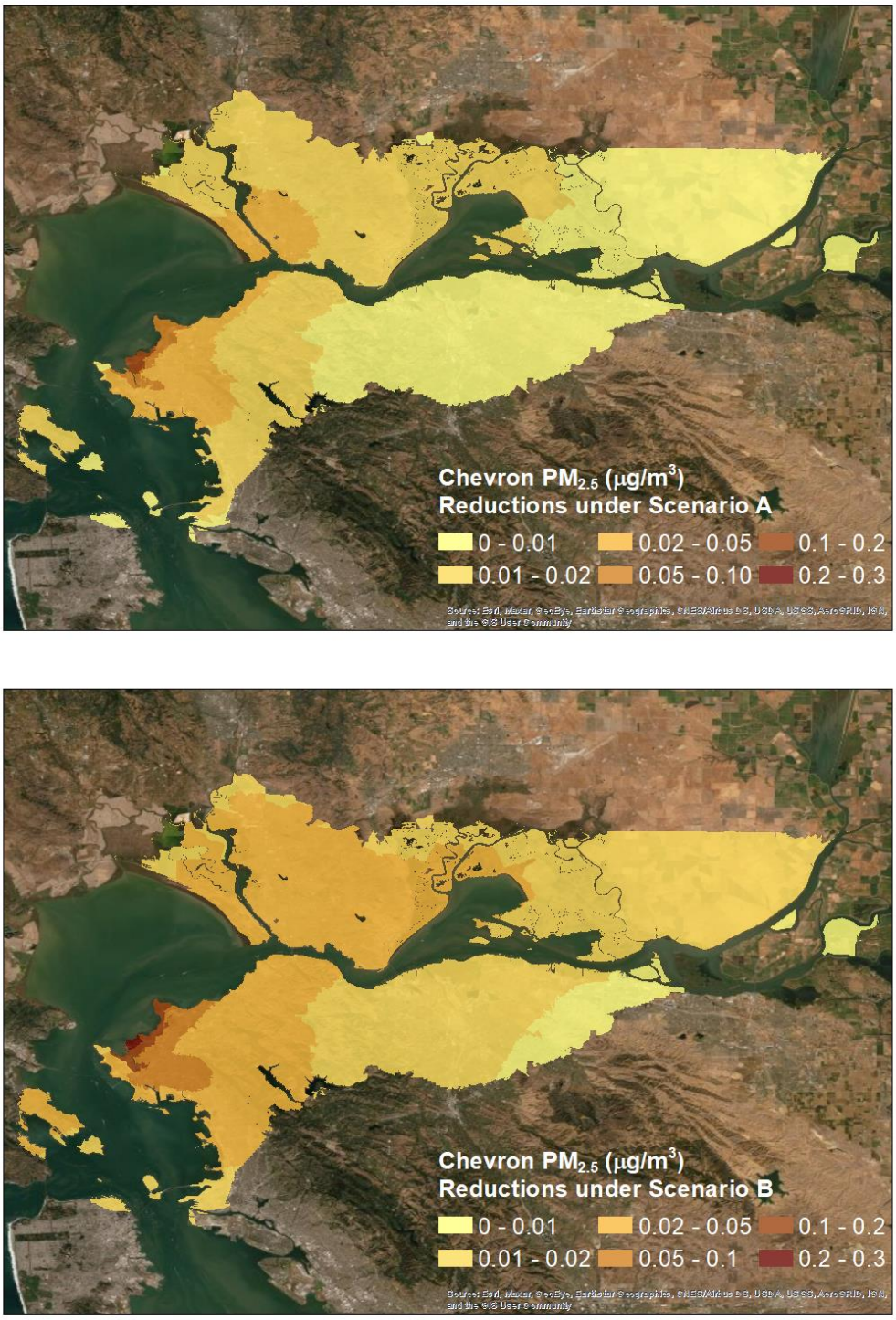

Figure 2.2: (a) Reductions in average $PM_{2.5}$ concentrations due to 0.020 gr/dscf standard (upper panel, Control Scenario A); (b) reductions in average $PM_{2.5}$ concentrations due to 0.010 gr/dscf standard (lower panel, Control Scenario B).

BenMAP–CE requires two sets of ambient concentrations to estimate health impacts. These are called base and control cases. CALPUFF simulations were designed to estimate: (1) the overall

health impacts of $PM_{2.5}$ emitted from the Chevron Richmond refinery, and (2) the benefits of reducing FCCU emissions under Control Scenario A and Control Scenario B. For estimating overall health impacts, the base case was the three-year average simulated $PM_{2.5}$ concentrations from all Chevron emissions, while the control case was simply an assumed concentration field with zero $PM_{2.5}$ (i.e., no emissions from Chevron) for comparison; the difference between these two cases provided a representation of the $PM_{2.5}$ contribution associated with total Chevron emissions.

For estimating the benefits of reducing FCCU emissions, the base case was the three-year average simulated $PM_{2.5}$ concentrations from uncontrolled FCCU emissions, while the control cases were the $PM_{2.5}$ concentration field resulting from the Control Scenario A and Control Scenario B emissions.

BenMAP–CE provides population data from the 2010 Census at both the Census block and Census tract levels. Block-average $PM_{2.5}$ contributions were assigned to each Census block in the study area. Figure 2.3 illustrates the set of such blocks. For details of the calculation of block averages, see Holstius and Martien, 2021.

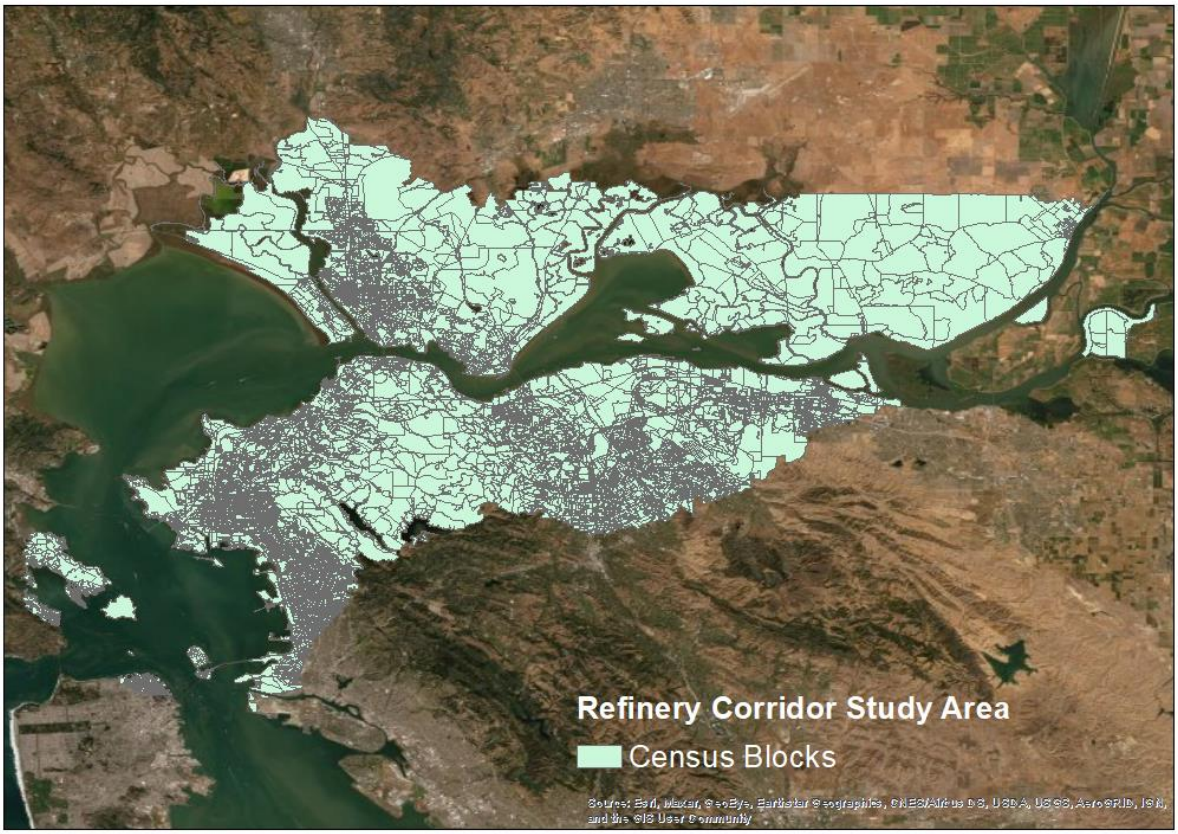

Figure 2.3: Map of the study area and all Census blocks included in the BenMAP–CE analysis.

2.3 Preparation of population data

BenMAP–CE requires population data to be grouped in a specific way to apply the available health impact functions. The developers of BenMAP–CE had already grouped the US Census Bureau's population data for this purpose for 2010, a year the most comprehensive census was conducted (Table 2.1). We projected the 2010 data to 2020 using an available module in BenMAP-CE, Figure 2.4.

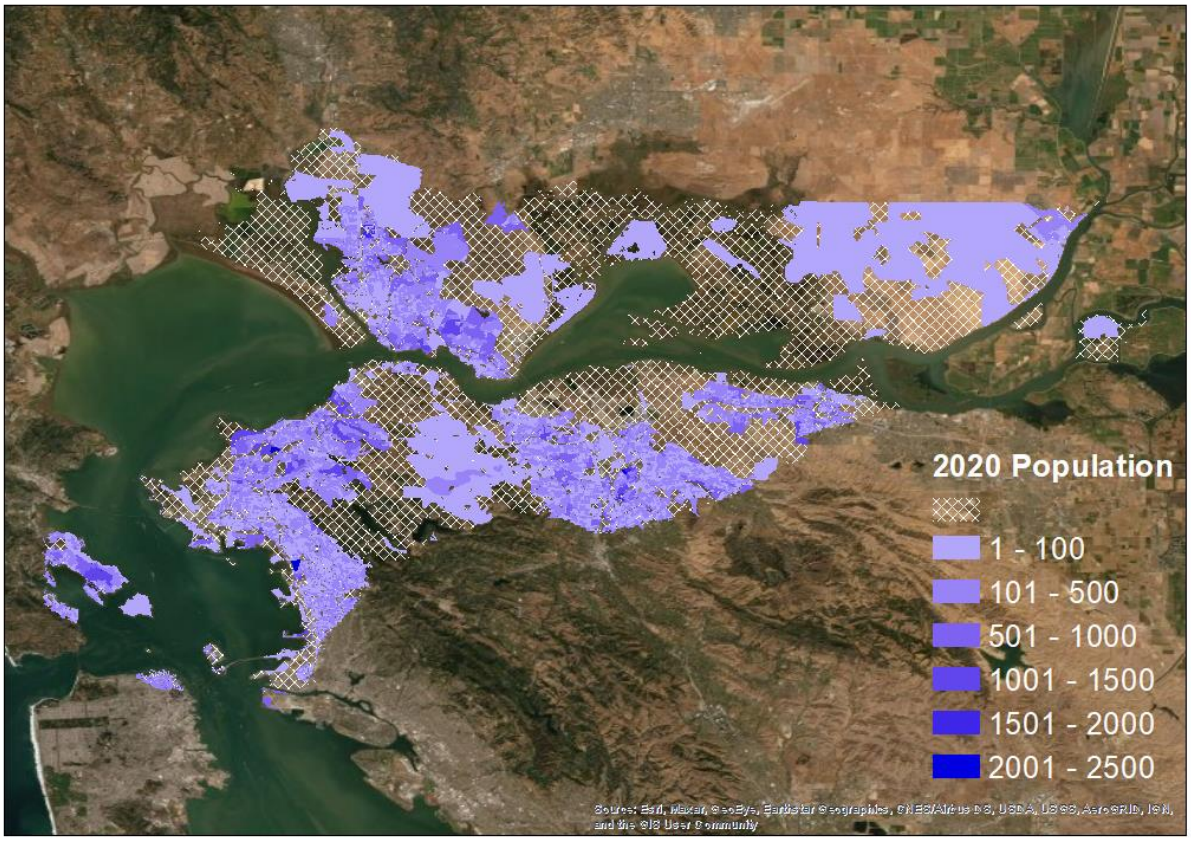

Figure 2.4: Projected 2020 population obtained by applying PopGrid to 2010 Census data.

As can be seen from Table 2.1, there were a total of 304 population groups for which $PM_{2.5}$ health impacts could be estimated. They comprised nineteen age, four race, two ethnic, and male and female groups (details of how these groups were established are provided in Appendix J of EPA 2018). BenMAP's racial classification schema is identical to that of the Center for Disease Control (CDC), from which BenMAP obtains baseline health data. CDC's schema is aligned with the US Census 2010 schema, except that multi-racial ("2 or more races," etc.) as well as "other race" responses are reclassified into one of these four "single-race" bins based on auxiliary data.[1] Thus, multiracial and other classifications have not been dropped; they have been reclassified into one of these four categories.

[1] This practice, termed "race bridging," is a convention followed by the CDC to support long-term trend analyses.

Table 2.1: BenMAP–CE population groupings.

Age	Race	Ethnicity	Sex
<1, 1–4, 5–9, 10–14, 15–19, 20–24, 25–29, 30–34, 35–39, 40–44, 45–49, 50–54, 55–59, 60–64, 65–69, 70–74, 75–79, 80–84, 85+	White African American Asian American Indian	Hispanic Non-Hispanic	Male Female

Application of BenMAP–CE

BenMAP–CE was applied for three different scenarios at the Census block level across the study area, as shown in Table 3.1. The first scenario, the baseline scenario, assessed the total impacts of $PM_{2.5}$ emitted from all modeled sources at the Chevron Richmond refinery. Scenarios A and B assessed reductions in these impacts due to achieving PM_{10} standards of 0.020 gr/dscf and 0.010 gr/dscf at the FCCU, respectively.

Table 3.1: BenMAP–CE application scenarios.

Scenario	Domain	Base Case	Control Case
Baseline	Study area (Census block level)	$PM_{2.5}$ emissions from all Chevron sources	All $PM_{2.5}$ concentrations set to zero (no emissions from Chevron)
A	Study area (Census block level)	$PM_{2.5}$ emissions from all Chevron sources	$PM_{2.5}$ emissions from all Chevron sources, but with FCCU emissions controlled to 0.020 gr/dscf standard
B	Study area (Census block level)	$PM_{2.5}$ emissions from all Chevron sources	$PM_{2.5}$ emissions from all Chevron sources, but with FCCU emissions controlled to 0.010 gr/dscf standard

BenMAP–CE was run using the same set of health impact functions used by the US EPA to assess $PM_{2.5}$ impacts in the United States, except for functions related to premature mortality. For the premature mortality category, we added three health impact functions to the EPA's set to ensure that the premature mortality endpoint was evaluated rigorously. Two of the added functions are from Jerrett et al., 2013 and are based on California-wide and nationwide analyses of a 1980–2000 cohort. The third added function is from Vodonos et al., 2018, which itself is a meta-analysis summarizing 53 single studies (including the three other studies that we included), 17 of which have been published since 2015.

Table 3.2 summarizes the health impact functions used in BenMAP–CE and also provides information on the health endpoints associated with each study, age range, and baseline health data used.

Table 3.2: Health endpoint, studies developed health impacts functions and epidemiological data used.

Health Endpoint	**Studies Developed Health Impacts Functions**	**Study Population**	**Baseline Health Data as Named in BenMAP–CE**
Cardiovascular			
Nonfatal heart attacks	Peters et al. (2001)	18+ years	Other incidence (2014)
	Pooled estimate: -Pope et al. (2006) -Sullivan et al. (2005) -Zanobetti et al. (2009) -Zanobetti and Schwartz (2006)	18+ years	Other incidence (2014)
Hospital admission, cardiovascular	Pooled estimate: -Zanobetti et al. (2009) -Peng et al. (2009) -Peng et al. (2008) -Bell et al. (2008)	64+ years	Other incidence (2014)
	Moolgavkar (2000)	18–64 years	Other incidence (2014)
Lost Work			
Work loss days	Ostro (1987)	18–65 years	Other incidence (2000)
Restricted Activity			
Minor restricted activity days	Ostro and Rothschild (1989)	18–65 years	Literature data
Asthma			
Asthma exacerbations	Pooled estimate: -Ostro et al. (2001) -Mar et al. (2004)	6–18 years	Prevalence (2008)

Health Endpoint	Studies Developed Health Impacts Functions	Study Population	Baseline Health Data as Named in BenMAP–CE
Asthma-related ER visits	Pooled estimate: -Mar et al. (2010) -Slaughter et al. (2005) -Glad et al. (2012)	All ages	Other incidence (2014)
Hospital admission, asthma	Pooled estimate: -Babin et al. (2007) -Sheppard (2003)	0–17 years	Other incidence (2014)
Respiratory illness			
Upper respiratory symptoms	Pope et al. (1991)	Asthmatics, 9–11 years	Prevalence (2008)
Lower respiratory symptoms	Schwartz and Neas (2000)	7–14 years	Literature data
Acute bronchitis	Dockery et al. (1996)	8–12 years	Other incidence (2000)
Hospital admission, chronic lung disease	Moolgavkar (2000)	18–64 years	Other incidence (2014)
Mortality			
Mortality, all-cause	Krewski et al. (2009) Lepeule et al. (2012) Woodruff et al. (1997)	30+ years 25+ years Infant (<1 year)	Mortality incidence (2020)
Mortality, all-cause (added to BenMAP–CE)	Jerrett et al. (2013) for CA Jerrett et al. (2013) for US Vodonos et al. (2018)	30+ years 30+ years All ages	Mortality incidence (2020)

Results

Results obtained from BenMAP–CE are tabulated in Table 4.1 using the US EPA's pooling method. This method allows users to summarize health and monetary impacts from changes in $PM_{2.5}$ concentrations. BenMAP–CE results showed that $PM_{2.5}$ emissions from the Chevron Richmond refinery result in 5.1 to 11.6 premature deaths per year, valued at 52.5 to 118 million US dollars. Achievement of the standards under Control Scenario A and Control Scenario B at the refinery's FCCU were estimated to reduce annual excess deaths by 13% and 23%, respectively, and result in benefits valued at 6.8 to 15.2 and 12.2 to 27.4 million dollars per

year, respectively. The range in the valuations shown, for both the baseline and the control benefits, is mostly attributable to the range in mortality impacts from the different health impact functions applied.

Table 4.1: Summary of health and monetary impacts of $PM_{2.5}$ from Chevron Richmond refinery emissions and percent change of FCCU emissions under Control Scenario A and Control Scenario B.

Baseline Health Impact[1] of Chevron Richmond Refinery (Annual)		Valuation[2] (Annual)	Reduction under Control Scenario A	Reduction under Control Scenario B
Cardiovascular	0.5–4.3 heart attacks	$63 k–$600 k	−13%	−22%
	1.0 hospital admissions	$47 k	−13%	−22%
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Asthma	200 exacerbations[3]	$12 k	−12%	−21%
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Mortality[5]	5.1–11.6 premature deaths	$52.5 M–$118 M	−13%	−23%
			$6.8 M/yr to $15.2 M/yr	**$12.2 M/yr to $27.4 M/yr**

[1] On the study population (about 1 million people)
[2] Conventional US EPA valuations, in 2015 US dollars
[3] Subset of pediatric (≤ 18 years)
[4] Other than asthma
[5] Including infant mortality
k, thousand; M, million.

Note that valued benefits shown in Table 4.1 represent US EPA's national average valuation, and were not modified specifically for the Bay Area.

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