Brake Pad Partnership

Air Deposition Modeling of Copper from Brake Pad Wear Debris in Castro Valley Creek Watershed

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1. Introduction

Dissolved copper (Cu) is an environmental concern because it is toxic to phytoplankton at the base of the aquatic food chain. There is also evidence that Cu may affect the sensory functions of certain fish species. California's South San Francisco Bay was designated an impaired water body under the U.S. Clean Water Act due to the presence of seven metals, including Cu. Cu enters the Bay via direct and indirect routes. Direct releases of Cu include the use of algaecides and leaching of antifouling coatings of marine vessels. Indirect releases include releases into other media that find their way into the watershed.

Brakes are considered to be a significant source of Cu entering the environment. Every time a driver applies the brake, friction material, which may contain Cu, is worn off and released either onto the vehicle, onto the road surface, or into the air. This work addresses the fate and transport of the fraction of material that is released into the air. Once emitted into the air, Cu-containing brake pad wear debris (BPWD) is dispersed by wind. Some portion of the BPWD is carried out of the region of concern, while some portion can eventually find its way into the watershed when it is deposited via wet and dry deposition onto waterbodies, or onto pervious and impervious surfaces within the watershed. As a part of the Brake Pad Partnership's efforts to quantify the contribution of vehicle BPWD to Cu concentrations in the San Francisco Bay environment, air modeling was undertaken to understand the transport and fate of BPWD in the atmosphere.

Figure 1 shows the role of air deposition modeling in the technical approach of Brake Pad Partnership. The goals of the atmospheric deposition modeling are two-fold. First, direct deposition fluxes to the bay are estimated, providing an input to the bay model. Second, estimated wet and dry deposition fluxes to pervious and impervious surfaces will be provided to the watershed models to simulate the migration of deposited Cu through the watershed.

The modeling approach and model setup and formulation are discussed in Section 2. The copper source loading estimates are used as emission inputs to the air deposition. Besides BPWD, industrial releases are the only other major source category that releases Cu into the air. Other parameters relevant for modeling the atmospheric behavior of BPWD are obtained from the physical and chemical characterization work. These input data are described in Section 3. With each input, the associated uncertainties were compiled to the extent possible. Section 4 provides a discussion of the results, including sensitivity studies of the estimated deposition fluxes to key uncertain inputs. Measurements of dry and wet deposition, combined with the sensitivity analysis, guided the development of a set of a posteriori results, which reproduced the behavior observed to an acceptable level of accuracy. The best estimates and uncertainty ranges of the air deposition fluxes are processed into suitable time and spatial resolutions for use in the watershed and bay models. Conclusions are provided in Section 5.

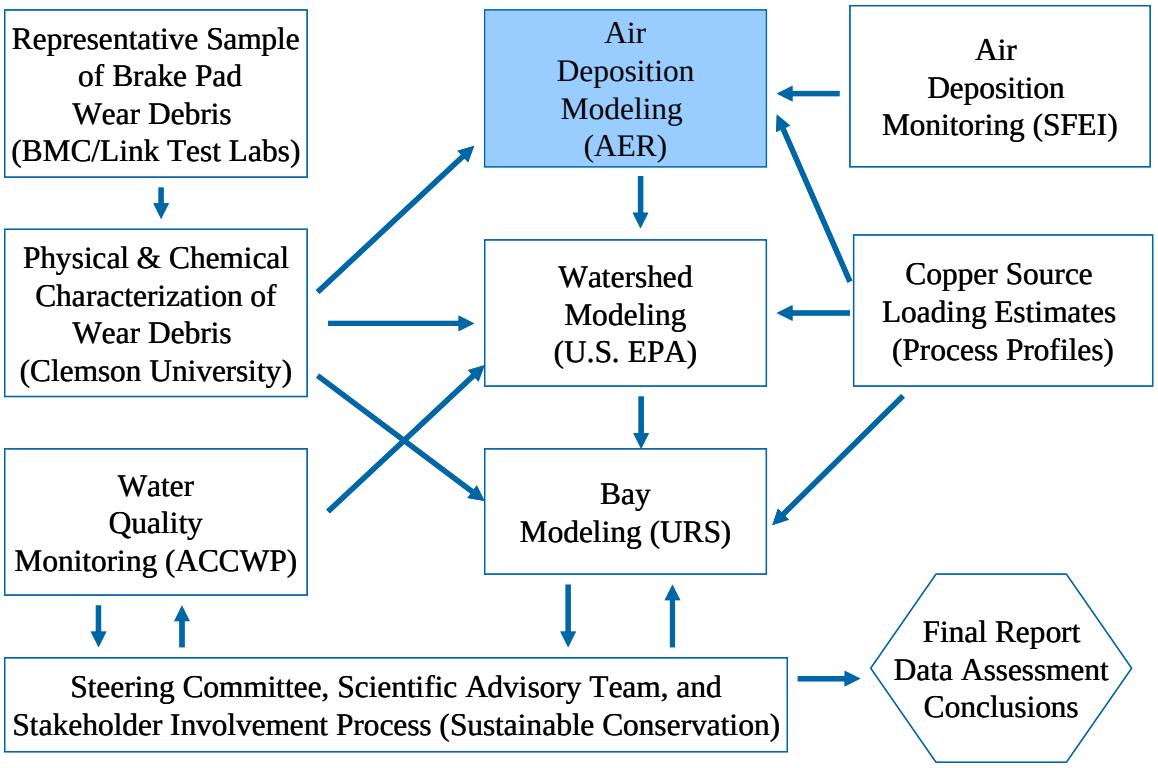

Figure 1. Brake Pad Partnership technical studies.

2. Model setup and formulation

2.1 Modeling approach

BPWD is emitted into the air as a population of particles of different sizes. According to Schaultman (2005, personal communication), the mass mean diameter of airborne BPWD particles is 3.5 microns (μm). Particles smaller than 0.5 microns and larger than 18 microns were observed in the laboratory. While coarse particles may deposit fairly close to the source, fine particles (aerodynamic diameter smaller than 2.5 μm) have an atmospheric lifetime of several days in the absence of precipitation and can be transported hundreds of km from the source. For the Castro Valley Creek subwatershed, BPWD may originate from local roadways (e.g., Highways 580 and surface streets in Castro Valley) or from other parts of the greater San Francisco Bay Area. This range of spatial scales needs to be taken into account in the modeling strategy. A multiscale approach was selected for this work, where a box model was used to simulate the regional background (excluding emissions from the Castro Valley watershed) and a detailed source-based dispersion model was used to simulate local impacts. Local impacts were simulated at a finer spatial resolution compared to the regional background. Both models use an internal time step of one-hour. Results from the regional and local models were summed for the Castro Valley watershed. For other locations, a scaled regional background (without emissions from that location) can be deduced based on the total emissions to be considered in the regional context. Scaled local impacts can then be added. The local results from Castro Valley will be scaled based on local emissions to represent the variability at different land use types based on the proximity to sources.

The detailed modeling approach is presented in Figure 2. The modeling procedure was designed to accomplish both the modeling and sensitivity study objectives of the Association of Bay Area Governments (ABAG)/BPP contract (Tasks 2-4 in the BPP contract).

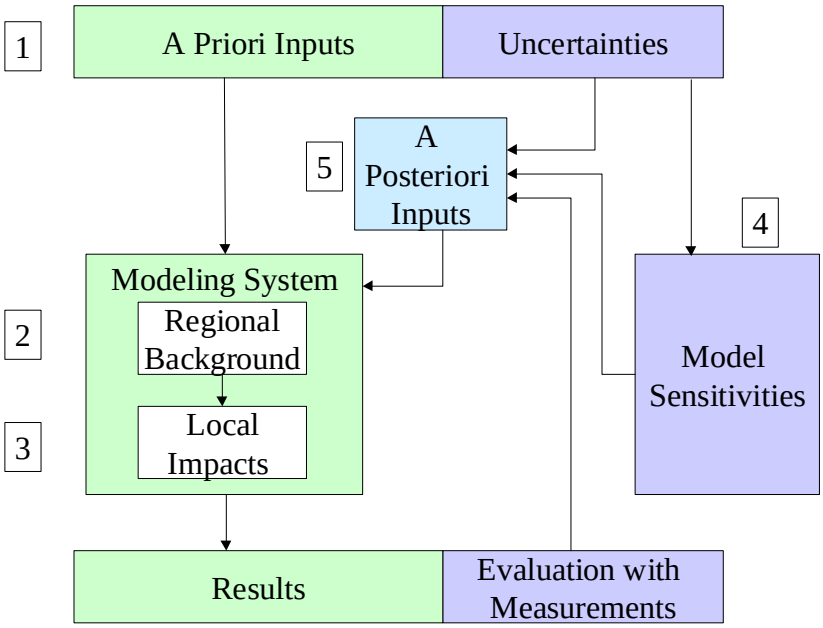

Figure 2. Air deposition modeling tasks

2.2 Modeling domains and periods

The study domain for air deposition modeling is the Castro Valley Creek subwatershed (see Figure 3) of the San Lorenzo Creek watershed. The Castro Valley Creek subwatershed, which covers a 5.5 square mile area including the unincorporated city of Castro Valley, is located in Alameda County and is considered to be quite representative of urban watersheds around the San Francisco Bay in terms of its landuse and other geographic characteristics.

For the purpose of air deposition modeling, the Castro Valley Creek subwatershed is part of the greater San Francisco Bay airshed, and concentrations of air pollutants in the Castro Valley area are affected by emissions elsewhere in the Bay Area. The wet and dry deposition fluxes contain a regional component from Bay Area emissions and a local component from emissions within the Castro Valley Creek subwatershed. To estimate the regional component of the BPWD deposition fluxes, a simple model of a well-mixed box was used, in which all Bay Area watersheds (see Figure 4) were represented.

A modeling period of one year (March 04 to February 05) was analyzed and compared to deposition measurements (Yee and Franz, 2005) available in the Castro Valley Creek subwatershed. Daily results were used in the comparison. For the best estimate case, both models were run for 5 years with daily varying meteorology so as to provide representative estimates for both wet and dry seasons for use in the watershed and bay models.

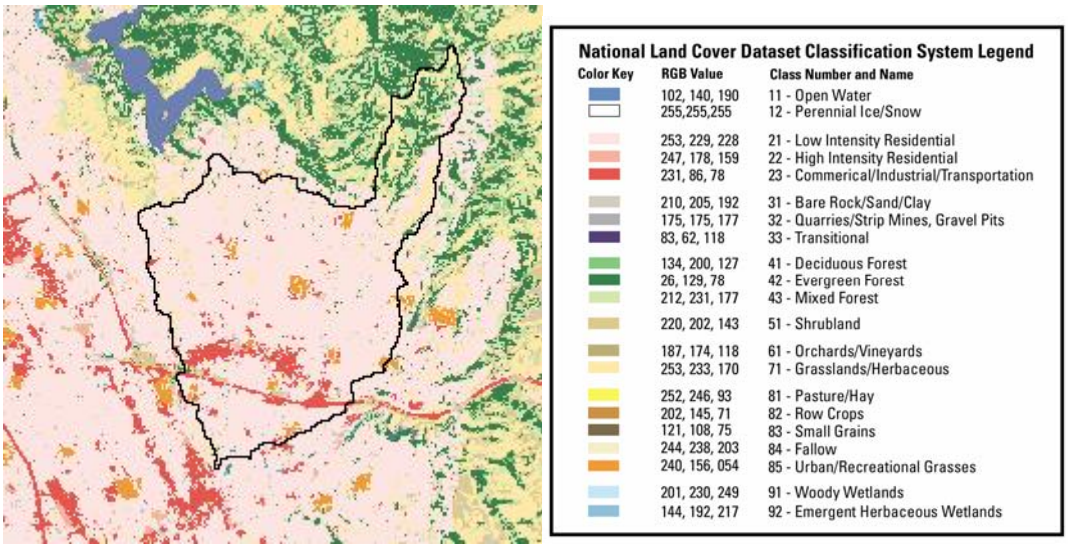

Figure 3. Castro Valley Creek subwatershed

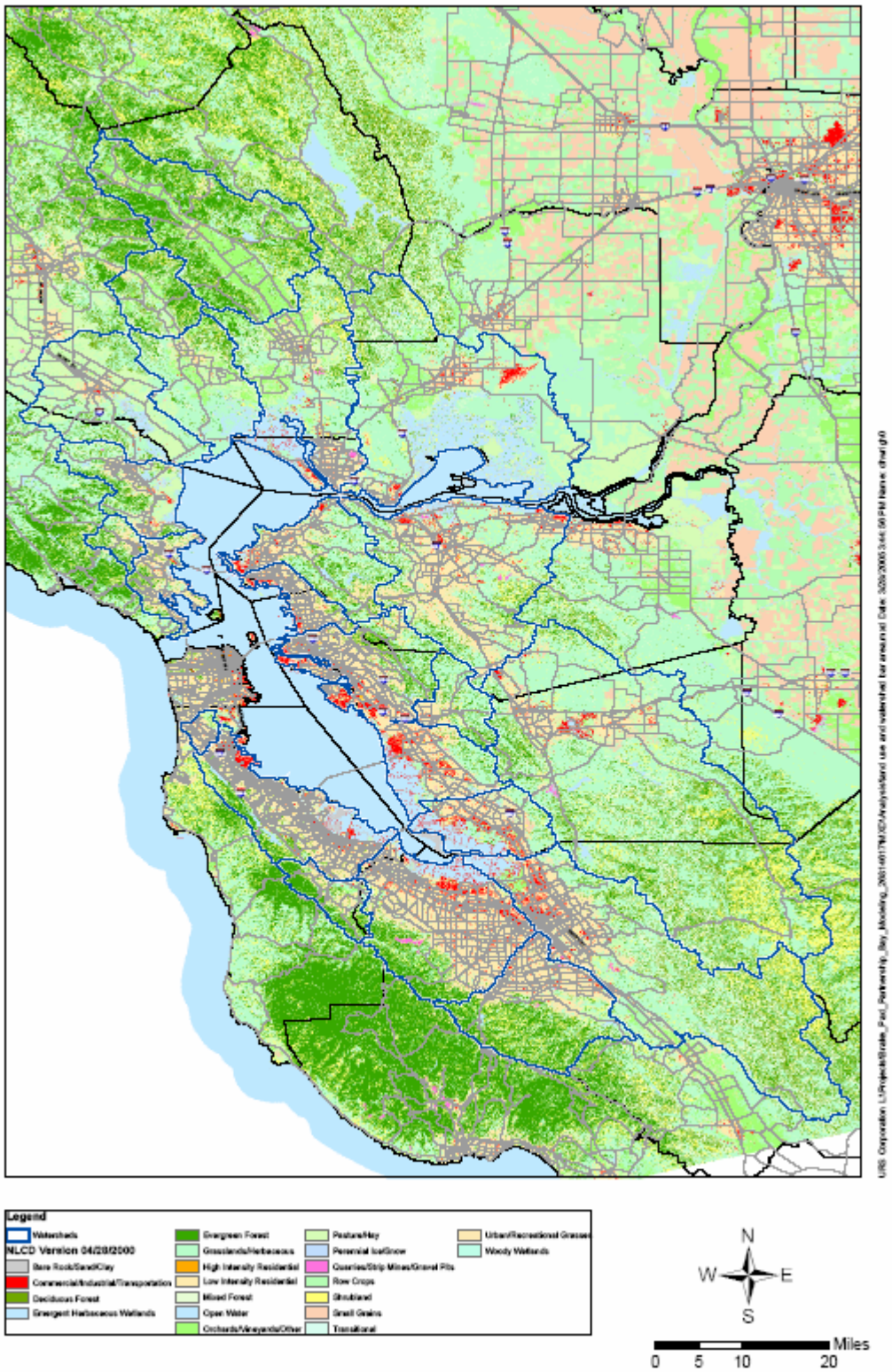

Figure 4. San Francisco Bay Area watersheds.

2.3 Model formulation

The box model (Pun and Seigneur, 2001) includes all significant physical transport processes that govern the atmospheric concentration and deposition fluxes of BPWD and its copper content. Such processes include dry deposition, wet deposition, emissions, horizontal transport, and vertical mixing. BPWD was treated as inert species in the simulations, with no chemical reactions and/or phase transition. Coagulation between BPWD and other particles was ignored. The formulations of wet and dry deposition have been improved over previous applications and are highlighted below.

The dry deposition flux, F_d ($\mu g/m^2/s$), is expressed as the product of the concentration of the species of interest, C ($\mu g/m^3$), and a deposition velocity, V_d (m/s).

$$F_d = C\ V_d \tag{1}$$

The following formulation is used for the dry deposition velocity of particles.

$$V_d = V_g + \frac{1}{r_a + r_b + r_a r_b V_g} \tag{2}$$

where r_a is the aerodynamic resistance, r_b is the quasi laminar layer resistance, and V_g is the particle settling velocity due to gravity. r_a is a function of meteorology, r_b is a function of the surface and particle characteristics, and V_g is a function of the particle size and density.

Wet deposition of particles is the result of two different processes: in-cloud scavenging (rainout) and below-cloud scavenging (precipitation scavenging or washout). In-cloud scavenging comprises nucleation scavenging (particles that act as cloud condensation nuclei growing into cloud droplets) and interstitial aerosol collection, which is a slow process (Seinfeld and Pandis, 1998). Because BPWD are emitted at the surface and we are studying their fate and transport in a limited domain (the Bay Area), BPWD are unlikely to be present in significant concentrations at cloud heights. Therefore, in-cloud scavenging was not considered important for BPWD in this study and we only considered washout as the wet deposition route.

The change of mass concentration of particles, C ($\mu g/m^3$), due to below-cloud scavenging during a rain event is modeled as follows:

$$dC / dt = - \Lambda\ C \tag{3}$$

where Λ (1/s) is the scavenging coefficient, which can be characterized as a function of rainfall intensity, rain drop size, and the size distribution of particles (Seinfeld and

Pandis, 1998, Figure 20.12). The formulation used in this study is consistent with the Industrial Source Complex Model (EPA, 1995), where Λ is the product of rainfall and a particle size-dependent parameter λ (Jindal and Heinold, 1991). Wet deposition estimates may be quite uncertain due to uncertainties in the size distribution characteristics of BPWD particles.

An important assumption made in this study is that only the fraction of BPWD that initially becomes airborne can remain airborne for a significant enough length of time to undergo atmospheric transport and deposition. (The fraction of BPWD that is directly released to the roadway is assumed to consist of coarse particles that would not be transported over long distances even if resuspended into the atmosphere.) The airborne BPWD that deposits on roadways is resuspended by moving traffic. Initially, deposited BPWD re-emissions were thought to be proportional to road dust emissions. Road dust emissions were estimated using an empirical formula based on EPA's AP-42 methodology (EPA, 2003):

$$E_{dust} = 1.8\ (sL / 2)^{0.65}\ (W/3)^{1.5} \qquad (4)$$

where E_{dust} is the $PM_{2.5}$ emission rate (lb/vehicle miles traveled, VMT) from vehicle traffic on a paved road (g /VMT); sL is the silt content (g/m^2) of road surface; and W is the average weight (tons) of vehicles traveling the road (which depends on traffic activity). Estimates of sL and W were obtained from the California Air Resources Board (CARB, 1997) for counties in the San Francisco Bay Area. VMT information was obtained from Rossolot (2005a). Hourly emissions were estimated based on a proportional relationship between the deposited BPWD flux and the silt content. There is currently no methodology to treat resuspension from surfaces other than paved and unpaved roads and agricultural surfaces, the latter two sources are expected to be smaller than the paved road resuspension term.

Since Equation 4 is empirical in nature, its applicability to the emissions of BPWD dust is highly uncertain. In fact, the empirical nature of Equation 4 requires no mass balance for silt and dust emissions, essentially assuming that there is a reservoir of silt on the roadways based on the assumption of a constant concentration (i.e., silt is continuously being generated by passing vehicles at the same time road dust is emitted by traffic). The same cannot be said about BPWD, because what is re-emitted must originate from BPWD emissions. A preliminary simulation was conducted to estimate the re-emissions of BPWD from deposited BPWD on roadways, considering only BPWD directly released to the air. This estimate indicated that all BPWD deposited on Bay Area roadways would be reemitted. Therefore, for the regional model, the resuspension term is simplified to contain a portion of the deposition that is proportional to the surface area occupied by roads compared to the total surface area.

Local impacts were estimated using the dispersion model ISC-ST version 3 (EPA, 1995). ISC-ST stands for the Industrial Source Complex (Short Term) model and is an EPA-approved model for local air dispersion modeling. While ISC was originally

developed to model industrial sources, EPA has also applied ISC for the modeling of urban areas (EPA, 1999).

ISC-ST is a computationally efficient model that treats transport, dispersion, dry deposition and wet deposition. The treatment of dry deposition in ISC-ST is similar to that presented in Equation 2. Wet deposition by below-cloud scavenging (washout) is treated in ISC-ST. The wet deposition flux (F_w) is defined as follows.

$$F_w = \int_z \lambda C dz \tag{5}$$

where C is the concentration of BPWD in the mixing layer, and λ (s^{-1}) is the scavenging coefficient. The scavenging coefficient is the product of the precipitation rate (mm/hr) and r_c, a scavenging parameter (hr/mm/s). r_c depends upon the particle size distribution and the nature of precipitation.

The ISC-ST model was not modified to treat re-emissions. Treatment of resuspended BPWD in this model using an iterative procedure will be discussed in the sensitivity studies section.

3. Input data

3.1 Airborne emissions of brake pad wear debris

The emissions of Cu from BPWD were estimated by Rossolot (2005a). However, for air deposition simulations, properties and concentrations of the Cu-containing particles of BPWD, and not Cu itself, dictate the wet and dry deposition behavior. Total air emissions of BPWD were obtained from Rossolot (2005b). For the regional model, Castro Valley Creek subwatershed emissions were excluded for the calculation of regional background. Industrial air emissions were included. Rossolot (2005c) estimated Cu emissions from industrial sources to be 359 kg / y in the Bay Area watersheds. No information was available regarding the characteristics of particles associated with industrial Cu emissions. Therefore, an assumption was made to relate Cu mass to particle mass using the same ratio as BPWD emissions (6%, see below). Table 1 summarizes the emission data used in the air deposition models.

Table 1. Emissions of Cu-containing particles used in the air deposition models.

Local model	**kg/y**
Castro Valley Creek subwatershed highway emissions	2,896
Castro Valley Creek subwatershed surface street emissions	1,648
Total Castro Valley Creek subwatershed emissions	**4,544**
Regional model	**kg/y**
Bay Area watersheds mobile source emissions (1)	781,848
Industrial emissions (2)	5,983
Total Bay Area watersheds emissions	**787,831**

(1) total watershed emissions 786,392 kg/y minus Castro Valley Creek subwatershed emissions 4,544 kg/y
(2) total Cu emissions 359 kg/y divided by an assumed particulate Cu content of 6%

Using the information in Table 2.1-6 of Rossolot (2005a) and the Kline McClintock approach for calculating uncertainties, the uncertainty in the emission factor of BPWD should be 0.1 mg/km (as compared to 0.2 mg /km for the Cu emission factor) for passenger vehicles. For medium and heavy duty vehicles (Table 2.2-2 and Table 2.3-2 of Rossolot, 2005a), the standard uncertainty is 0.26 mg/km and 0.14 mg/km for BPWD, respectively (compared to 0.4 and 0.2 mg /km for the emission factors for Cu). The emission of Cu represents 6% of the emissions of BPWD, but is associated with a larger absolute value of standard uncertainty. Therefore, the uncertainty associated with Cu deposition should be dominated by the uncertainty in the mass fraction number (see below). Nonetheless, the uncertainties of BPWD emissions were 33% in the bay area airshed and 31% in the Castro Valley Creek subwatershed (K. Rossolot, August 2005, personal communication); these uncertainties are investigated in a sensitivity study.

The mass fraction of Cu in BPWD was needed to convert the modeled quantities to concentrations and fluxes of Cu for comparison with deposition data. Rossolot

(2005b) compared the BPWD emissions and Cu emissions (Rossolot, 2005a) and determined that BPWD contains an average of 6% Cu. This mass fraction was consistent with the nominal values (± standard uncertainty) of 9 (±4)% and 5 (±3)%, respectively, for factory and non-factory brake pads lining materials. The Cu content in BPWD may differ from that of the lining material because a fraction of the brake pad lining material volatilizes during braking and the BPWD includes wear material from the rotor or the other member of the friction couple. Nonetheless, the uncertainty range seemed applicable. Therefore, a nominal value of 6% was used with a standard uncertainty of 4% when converting BPWD deposition estimates to Cu deposition estimates.

The fine resolution domain covered the Castro Valley Creek subwatershed. Line sources (represented by elongated area sources in ISC) were used for highways and area sources were used for traffic distributed on surface streets. Due to the availability of emission estimates, only a portion of I-580 (running E-W) was included at the southern end of the domain as a highway source. For spatial allocation of the highway emissions within the fine-resolution domain, a Geographic Information System (GIS) approach was used, together with location data based on the U.S. Census Bureau's 2000 Tiger Line Transportation Layer for U.S. highways. An average road width was estimated based on the number of traffic lanes on I-580 in Castro Valley. A sensitivity study was carried out to test the sensitivity to the spatial allocation of the emissions. The highway emissions were doubled within the fine grid domain with a corresponding decrease in the regional domain. The increased highway emissions were added to approximate highway emissions from the stretch of I-580 running SE-NW to the west of Castro Valley Creek subwatershed.

For temporal allocation, the default allocation was a uniform distribution due to a lack of seasonal, monthly, day-of-the-week or hour-of-the-day specific emission information. Highway traffic tends to be more congested during weekdays than during weekends. Chinkin et al. (2003) found that in Los Angeles, traffic activity of passenger vehicles decreased by 15-20% on weekend days compared to weekdays, while VMT of heavy duty vehicle decreased by 40-80%. Assuming that the emissions of BPWD were proportional to the activity pattern for each vehicle class, weekday vs. weekend brake emissions were estimated (shown in Table 2) and these values were used in a sensitivity study.

Table 2. Weekday vs. weekend emissions of BPWD

Emissions (kg/day)	Bay area watersheds		Castro Valley Creek subwatershed I 580		Castro Valley Creek subwatershed surface streets	
	weekday	weekend	weekday	weekend	weekday	weekend
Passenger + medium duty vehicles (1)	1698	1358	6.15	4.92	3.50	2.80
Heavy duty vehicles (2)	668	267	2.57	1.03	1.46	0.59
Total	2366	1626	8.73	5.95	4.97	3.39

(1) Weekend traffic activity assumed to decrease by 20% over weekday levels for passenger vehicles and medium duty vehicles
(2) Weekend traffic activity assumed to decrease by 60% over weekday levels for heavy duty vehicles

As described in Section 2, in the regional model, all BPWD deposited on roadways was expected to undergo re-emissions. Hence, re-emissions were modeled as a fraction of the deposition fluxes. The fraction was determined by the fraction of road surface vs. total surface area in the Bay Area modeling domain and was nominally 3.3% (T. Cooke, personal communication, August 2005). For the fine grid modeling, the re-emission term on highways is 100% of the air deposition flux resulting from direct air emissions. Remissions on surface streets, represented by an area source, will be 8% of the deposition flux, which is the fraction of street surface to total surface area in the Castro Valley Creek subwatershed (T. Cooke, personal communication, August 2005). The net air deposition fluxes on the highway and other road surfaces would be zero after re-emissions is taken into account. An upper limit estimate of the air deposition fluxes to road surfaces was obtained when re-emissions was not treated in the base case. Fluxes at receptors next to roads or on top of buildings would be affected by direct and re-emissions of BPWD. For those sites, re-emissions were treated as a sensitivity case in the local scale simulation (see the Section 4).

3.2 Terrain data

Elevations of the sources and receptors were derived from the USGS 10-meter Hayward 7.5' Quadrangle Digital Elevation Model file. This elevation file was also used as an input file to the model. ISC uses this information to calculate the depletion of plume material due to dry deposition along the path from source to receptor.

3.3 Receptor locations

The locations in latitude/longitude coordinates of receptors were provided by Donald Yee of the San Francisco Estuary Institute.

3.4 Meteorological data

ISC-ST3 requires hourly meteorological data as one of the basic model inputs. The inputs required include temperature, pressure, relative humidity, precipitation, wind speed, wind direction, stability category, mixing height, surface roughness length, Monin-Obukhov length, and surface friction velocity.

Surface meteorology information was derived from three sources: the National Climatic Data Center (NCDC) Integrated Surface Hourly data format file for the Hayward Air Terminal, the NCDC Local Climatological Data format file for the Hayward Air Terminal, and the RAWS data from the Western Regional Climatological Center for the Las Trampas monitoring station. Upper air soundings were obtained from the NOAA Forecast Systems Laboratory radiosonde measurements at the Oakland Airport.

In order to convert the raw data from various sources to the format required by ISC-ST3, two EPA meteorological pre-processors were used. The first was the Mixing Height processor, which converts surface and upper air data into twice daily mixing height estimates. The Meteorological Processor for Regulatory Models (MPRM) was then used to combine surface data and mixing height data to create the hourly meteorological file required for ISC.

Of the meteorological variables, rainfall was expected to be the most geographically variable. The California Irrigation Management Information System (CIMIS) of the California Department of Water Resources (DWR) manages a network of over 120 automated weather stations in the state of California. http://wwwcimis.water.ca.gov/cimis/welcome.jsp was identified as an alternative source of rainfall data (Arleen Fang, personal communication 13 July 2005). We downloaded data from the Union City station (July 2005) as an alternative dataset use in the fine-resolution modeling.

3.5 Characteristics of BPWD

The characteristics of BPWD particles dictate their behavior in the deposition process. Important particle characteristics include the particle size and particle density. Both parameters affect the gravitational settling velocity (V_g) of particles. The particle size also affects the wet scavenging coefficient (Λ). The particle size distribution was represented explicitly as mass fraction in each size range in the fine resolution model. The coarse resolution model used a more simplistic representation using only the mass median diameter.

Based on Haselden et al. (2004), Rossolot (2005a) recommended the size distribution shown in Table 3 for describing BPWD. The mode of the size distribution is in the 3.2 to 5.6 μm size range. The mass median aerodynamic diameter of the airborne fraction of the hypothetical representative brake pad material was determined by

Schaultman (personal communication, August 2005) to be approximately 3.5 μm (using the geometric mean size of each range). This value is larger than the measurements of Garg et al. (2000) (0.6 to 2.5 μm) but smaller than those of Sanders et al. (2003) (3.9 to 7.2 μm).

Table 3. Particle size distribution for use in modeling (Haselden et al, 2004).

Particle size range, μm	Geometric mean size (μm)	% of total particles	% of copper particles
all particles	23.81	100.00 ± 5.39	100.00 ± 8.47
10 - 18	13.42	93.80 ± 5.20	94.76 ± 7.91
5.6 - 10	7.48	88.65 ± 5.02	91.18 ± 7.73
3.2 – 5.6	4.23	70.88 ± 4.46	74.66 ± 6.72
1.8 – 3.2	2.40	44.48 ± 3.45	46.23 ± 5.00
1.0 – 1.8	1.34	24.74 ± 2.87	31.97 ± 3.99
0.56 – 1	0.748	12.11 ± 2.37	15.76 ± 2.87
0.32 – 0.56	0.423	6.84 ± 1.76	9.42 ± 1.80
0.18 – 0.32	0.240	2.62 ± 1.60	4.62 ± 1.55
0.1 – 0.18	0.134	0.77 ± 1.25	2.01 ± 1.39
0.056 - 0.1	0.075	0.50 ± 0.73	0.25 ± 1.02
<0.056	0.042	0.50 ± 0.42	0.05 ± 0.61

Uncertainties of the particle size distribution were compiled by Haselden et al. (as shown in Table 3). When constructing an alternative particle size distribution, mass balance needed to be taken into account. Complicating the analysis further, cutoff sizes at the stages of the MOUDI instrument are not perfect. At a given stage, some particles larger than the lower cutoff of the previous stage will be collected and particles smaller than the lower limit of the current stage may also deposit. In the base case, we used the upper cutoff as the characteristic size for a range of particle sizes that was collected in a single bin. A sensitivity test was constructed by relabelling each size bin using the lower cut off size rather than the upper cut off size. The mass median diameter was decreased from the nominal value of 3.5 μm to 3.1 μm in the sensitivity simulation (M. Schaultman, personal communication, August 2005), with a Λ value of 2.0×10^{-4} h/mm/s (decreased from the nominal value of 2.4×10^{-4} h/mm/s).

Trainer (2001) reported a value of 2.98 g/cm^3 for BPWD, and Sanders et al. (2002) measured a range of 2.32 to 2.94 g/cm^3 for different brake materials. One study (Ford) estimated a density of 5 g/cm^3. We used a nominal value of 3 g/cm^3 in the models. A sensitivity study was conducted using the higher density of 5 g/cm^3.

4. Results

Table 4 summarizes the model runs. Runs 1 through 8 were designed to analyze data uncertainties as discussed in Section 3. Runs 9 through 12 were conducted to test some key assumptions and to provide additional information for the analysis of the results.

Table 4. List of model runs.

Run number	Description	Changes with respect to the nominal base run
1	Base case	A range of copper content (6%±4%) applied to bound uncertainties in estimating copper deposition based on modeled fluxes of deposition of BPWD particles
2	Treatment of re-emissions in the local scale model	Re-emissions estimated from base case run; iterative run performed with direct + reemissions
3.	Uncertain particle size and distribution	Alternative description of particle size distribution, with a lower mass mean diameter (and reduced Λ for regional simulation)
4.	Meteorology	Alternative rainfall data; either as input to model or used to scale output
5.	Air emission factor of BPWD	Increased of 30%
6.	Domain allocation	Additional emissions sources included in the fine resolution domain
7.	Temporal profile	Weekday vs. weekend day emissions
8.	Particle density	Increased from 3 g/cm^3 to 5 g/cm^3
9.	Sources of BPWD	Highway emissions only
10.	Redistributing surface emissions of BPWD	Spreading out surface emissions over entire watershed instead of only areas with high density of roads
11.	Doubling surface emissions of BPWD	Braking per mile should be higher on surface streets than on highways
12.	Elevation of highway emissions	Increase elevation to account for the presence of sound wall (10-16 ft)

4.1 Base case results

Results for wet deposition of copper in the base case simulation are compared to the observed deposition in Figure 5. Data were available at two monitoring sites, Castro Valley Community Center (CVCC) and Castro Valley Elementary School (CVE). On average, wet deposition fluxes were well represented by the model. The average observed wet deposition flux at CVCC was 2.15 $\mu g/m^2$ for seven two-week samples and

the average simulated flux was 1.77 $\mu g/m^2$. Wet deposition measurements from ten two-week periods averaged to be 2.11 $\mu g/m^2$ at CVE, with a corresponding modeled flux of 2.44 $\mu g/m^2$. Limiting the CVE data set to only periods with corresponding measurements at CVCC, the seven-period average was 2.24 $\mu g/m^2$, with a corresponding prediction of 1.94 $\mu g/m^2$. Therefore, on average, similar wet deposition fluxes were recorded and simulated at CVCC and CVE.

During individual periods, the model over- or underpredicted wet deposition fluxes. Comparing the data taken at CVCC and CVE, it can be seen that the measurements displayed higher variability than the model, which tended to predict fairly similar results for these two sites (Figure 6). Wet deposition fluxes depend on rainfall and atmospheric concentrations. Rainfall was quite similar at CVE and CVCC for many of these periods. Therefore, spatial variability was likely present in the concentrations of BPWD concentrations that was not represented by the model. Several examples are discussed below:

- A period with significant underprediction occurred during 17 November to 3 December 2004. Measured wet deposition fluxes were 1.0 $\mu g/m^2$ (13 mm rain) to 1.5 $\mu g/m^2$ (12 mm rain) at CVE and CVCC, from Yee and Franz (2005). Simulated wet deposition fluxes were 0.5 $\mu g/m^2$at CVE and 0.4 $\mu g/m^2$ at CVCC.
- On an absolute basis, the most significant underprediction was seen for the 17-31 March 2004 period. Based on Yee and Franz (2005), cumulative rainfall for 17-31 March 2004 was 17 and 18 mm at CVCC and CVE, respectively. Therefore, the differences in the observed wet deposition flux (CVCC > CVE by a factor of 2.8) must have been due to different amount of copper-containing particles entrained in the raindrops.
- During 9-23 February 2005, the observed wet deposition flux was higher at CVE compared to CVCC by a factor of two (rainfall recorded at these sites differed by only 20%). The relatively uniform flux predicted by the model matched the higher flux at CVE very well, but overpredicted the CVCC observation.

On average and during many measurement periods, modeled wet deposition fluxes contained a strong regional component. In fact, during the 3-17 December 2004 and 29 December 2004-12 January 2005 periods, the regional components of copper deposition were modeled to exceed the total observed deposition fluxes (Figure 7). The regional component accounted for 82% of the average modeled deposition flux at CVCC, and 75% at CVE on days corresponding to measurements. The modeling results seemed to be consistent with the locations of these two sites, with CVE closer to I580 and busy surface streets in Castro Valley than CVCC.

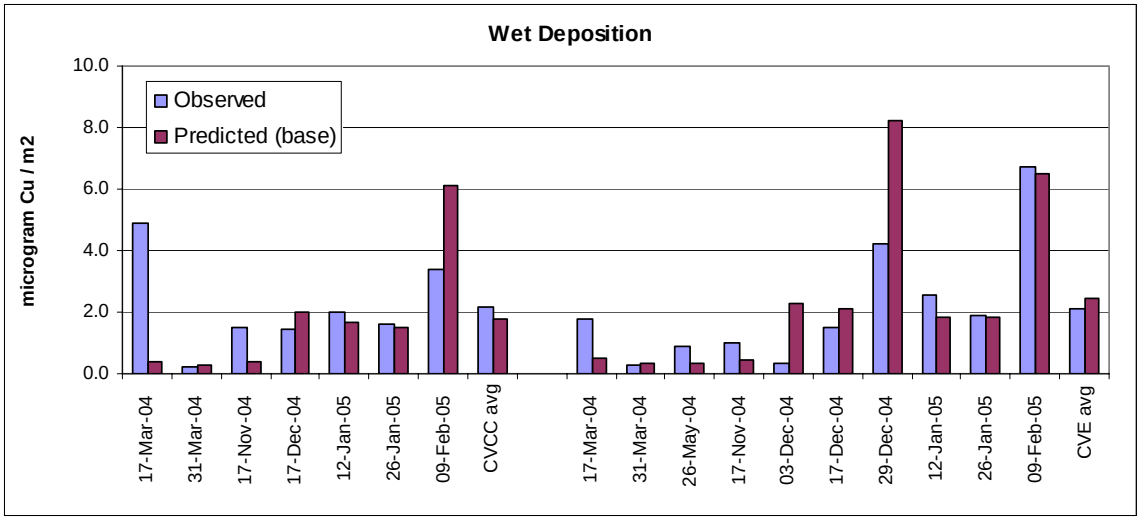

Figure 5. Comparison of observed and predicted Cu wet deposition fluxes at CVCC (left side) and CVE (right side).

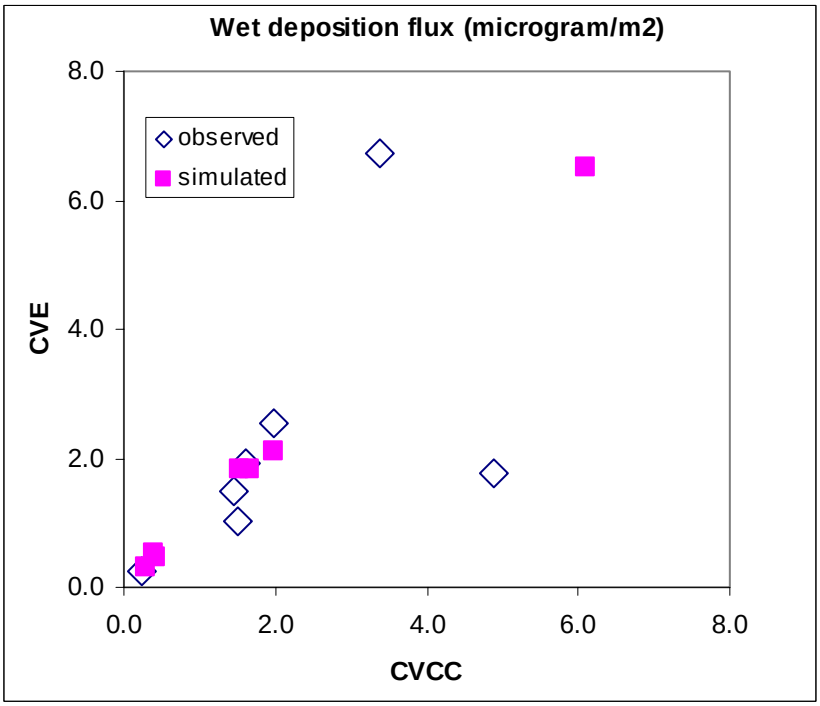

Figure 6. Measured and modeled Cu wet deposition fluxes at CVCC and CVE corresponding to matching sampling times.

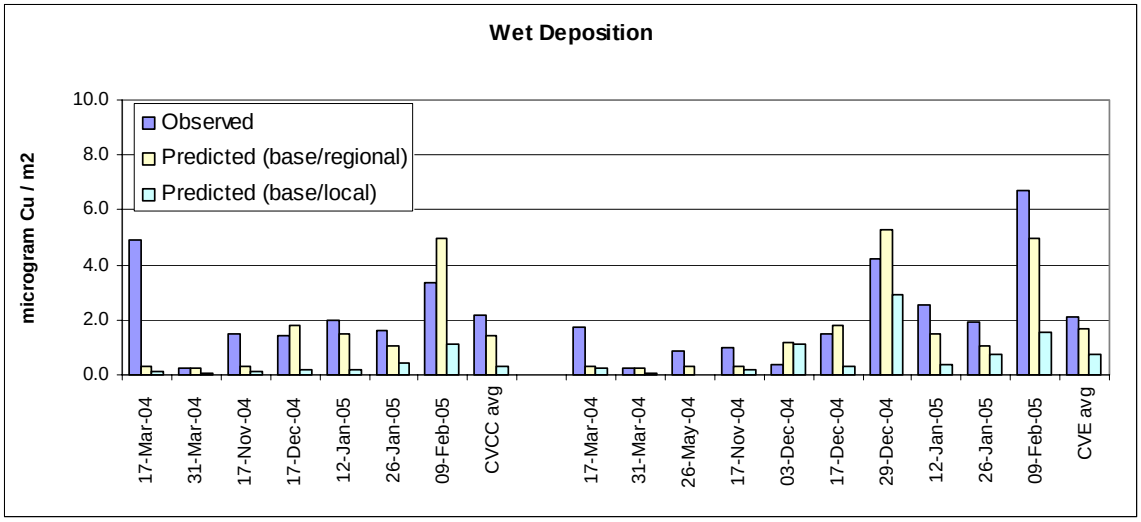

Figure 7. Observed Cu wet deposition fluxes and predicted regional and local contributions to Cu wet deposition fluxes at CVCC (left side) and CVE (right side).

Model performance for dry deposition fluxes was considerably less satisfactory than for wet deposition fluxes. Measured dry deposition fluxes averaged to be 28.9 $\mu g/m^2$ at Redwood, 14.5 $\mu g/m^2$ to 17 $\mu g/m^2$ at CVE and CVCC, and 8.8 $\mu g/m^2$ at Madison. The model overpredicted the average dry deposition flux at Redwood by a factor of 2.8. However, at sites that are less impacted by traffic emissions, dry deposition fluxes were underpredicted. At CVCC and CVE, the predicted dry deposition fluxes represented 52-57% of the measured fluxes. At Madison, which is farthest from the highway and major roads, the model predicted on average only 11% of the observed dry deposition of Cu. In sum, the model predicted a much stronger gradient for dry deposition fluxes than was observed (Figure 8).

Unlike wet deposition fluxes, local influence was predicted to be much stronger on the dry deposition fluxes compared to the regional fluxes at CVCC and CVE. Regional fluxes accounted for 10 to 17% at these mid-watershed sites. At Redwood, dry deposition fluxes were controlled by local emissions. At the Madison site, deposition was predicted to be regional in nature; local emissions did not affect the simulated dry deposition fluxes. Using the results of Case number 9, it was also concluded that simulated deposition fluxes at the Redwood site originated predominantly from highway emissions. Modeled deposition fluxes at CVCC and CVE originated predominantly from surface road emissions. From these results, it was concluded that local sources, including highway and surface streets, have limited range of influence on dry deposition fluxes.

These results indicated that the model underpredicted either the regional or local or both components of dry deposition fluxes at sites that are relatively far away from major sources, but overestimated the local component at sites like Redwood that were very close to major sources of brake wear debris (see the sensitivity section for further discussion).

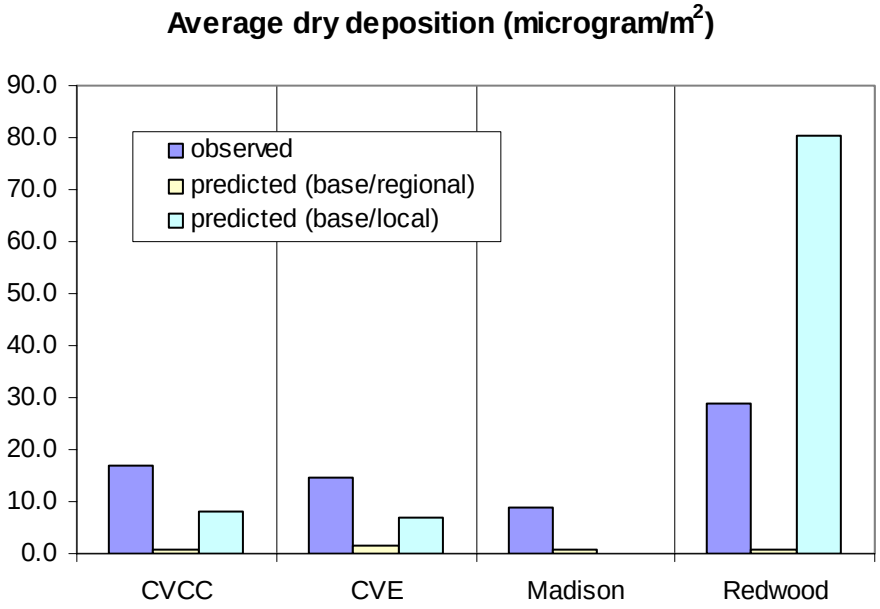

Figure 8. Observed Cu dry deposition fluxes and predicted regional and local contributions to Cu dry deposition fluxes at CVCC, CVE, Madison, and Redwood.

4.2 Sensitivity cases

4.2.1 Copper content

The content of copper in BPWD was determined to be a major source of uncertainty in the estimates of airborne emissions of Cu from brake wear (Rossolot, 2005a). A range of Cu contents corresponding to nominal (6%) ± standard uncertainty (4%) was used to determine the sensitivity of the air deposition modeling results to this parameter. The range of predicted wet deposition fluxes is presented in Figure 9 as error bars to the base case simulated values. The uncertainty in the predictions due to Cu content was significant enough that most of the observed fluxes lied within the range of predicted values.

Despite the overprediction at the Redwood site, model predictions were nonetheless consistent with the observed data within uncertainties due to Cu contents. However, at CVE, CVCC, and Madison, observed values were above the error bars of the modeled fluxes, indicating that other sources of uncertainties dominated those dry deposition predictions.

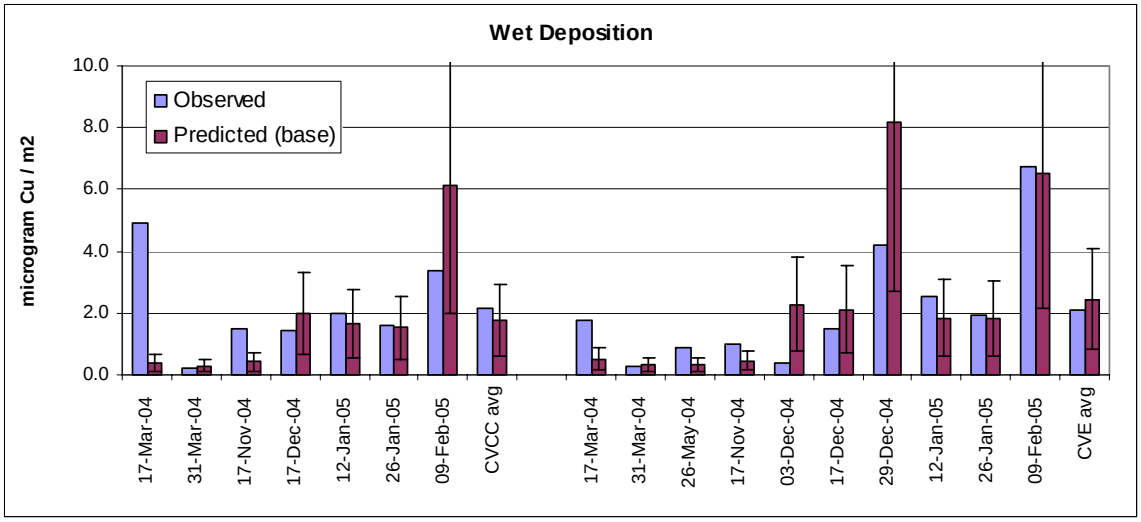

Figure 9. Comparison of observed and predicted Cu wet deposition fluxes ± uncertainty due to Cu content of BPWD at CVCC (left side) and CVE (right side).

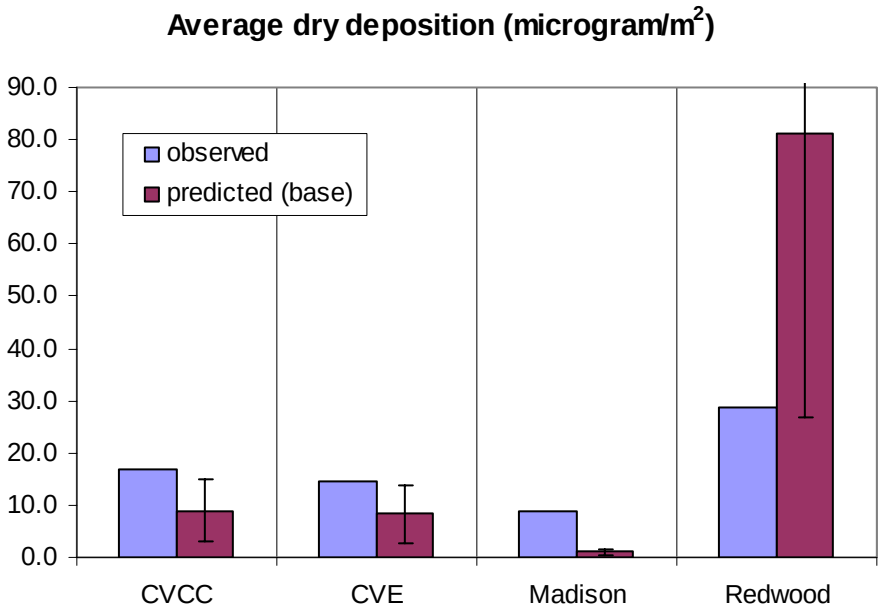

Figure 10. Observed Cu dry deposition fluxes and predicted Cu dry deposition fluxes ± uncertainty due to Cu content of BPWD at CVCC, CVE, Madison, and Redwood.

4.2.2 Rainfall

Rainfall is a highly heterogeneous quantity. At a given site, the comparison between measured and modeled wet deposition fluxes is highly sensitive to the accuracy of the rainfall data used by the model. For example, if the meteorological data used in the model indicated a lack of rain when there was in fact rain, the predicted wet

deposition flux would be zero compared to a non-zero observed value. Indirectly, the amount of BPWD deposited due to wet deposition affects concentrations in the atmosphere and the dry and wet deposition fluxes during the subsequent time steps.

Rainfall data from Union City were used in a sensitivity run. For individual periods, the predictions can improve or degrade. There was no obvious advantage for using data from Union City instead of Hayward Airport (Figure 11).

For individual periods, we investigated the scaling of wet deposition fluxes by more localized measurements of rainfall. We used measurements from Bellingham Drive, Castro Valley and rainfall measured at the samplers for this purpose. (These data could not be used in the modeling run because a continuous rainfall record could not be obtained.) The Bellingham Drive monitor, being at higher elevation, recorded more rain than the other rain measurements considered. For the 26 January – 9 February 2005, scaling using the Bellingham Drive rainfall data led to significant overpredictions. For other periods when the model overpredicted wet deposition fluxes, scaling the wet deposition predictions using Bellingham Drive data generally did not improve model performance (e.g., periods starting 29 December 2004 and 9 February 2005).

A priori, the highest likelihood of improvement would be to scale predictions using precipitation data obtained with wet deposition measurements. However, this did not seem to be the case, perhaps because the rainfall measurements from a wet deposition sampler are not equivalent to those obtained using a rain gauge. Some examples are provided below (see Figure 11).

- During 17 November to 3 December 2004, measured wet deposition fluxes were 1.0 $\mu g/m^2$ to 1.5 $\mu g/m^2$ at CVE and CVCC. Simulated wet deposition fluxes were 0.5 $\mu g/m^2$ at CVE and 0.4 $\mu g/m^2$ at CVCC. Rainfall data used in modeling indicated only 6.2 mm rain at Hayward airport, as opposed to 13 mm at CVE and 12 mm at CVCC. The lower rainfall amount used in the models compared to the observations could explain the underprediction at CVE but not at CVCC.
- Cumulative rainfall for 17-31 March 2004 was 17 and 18 mm at CVCC and CVE, respectively (rainfall used in the models was 10.4 mm, responsible for some but not all of the underpredictions by the model). Therefore, the models were unable to reproduce the observed wet deposition fluxes even after scaling.
- The models significantly overpredicted wet deposition fluxes at CVE during the 3-17 December 2004 and 29 December 2004 – 12 January 2005 periods. Rainfall recorded at CVE was 61 mm and 112 mm for 3-17 December 2004 and 29 December 2004 – 12 January 2005, respectively. Rainfall data used in simulation were 48.5 mm and 97.6 mm, respectively, for those periods. In both these instances, the difference in the rainfall data did not explain the model overprediction.

From these examples, it was concluded that rainfall data were not the most important source of uncertainty in the predicted wet deposition fluxes for some periods. Uncertainties were present in the modeling of the atmospheric concentrations (including

variability, as discussed in the previous section) and/or the scavenging process of atmospheric particles.

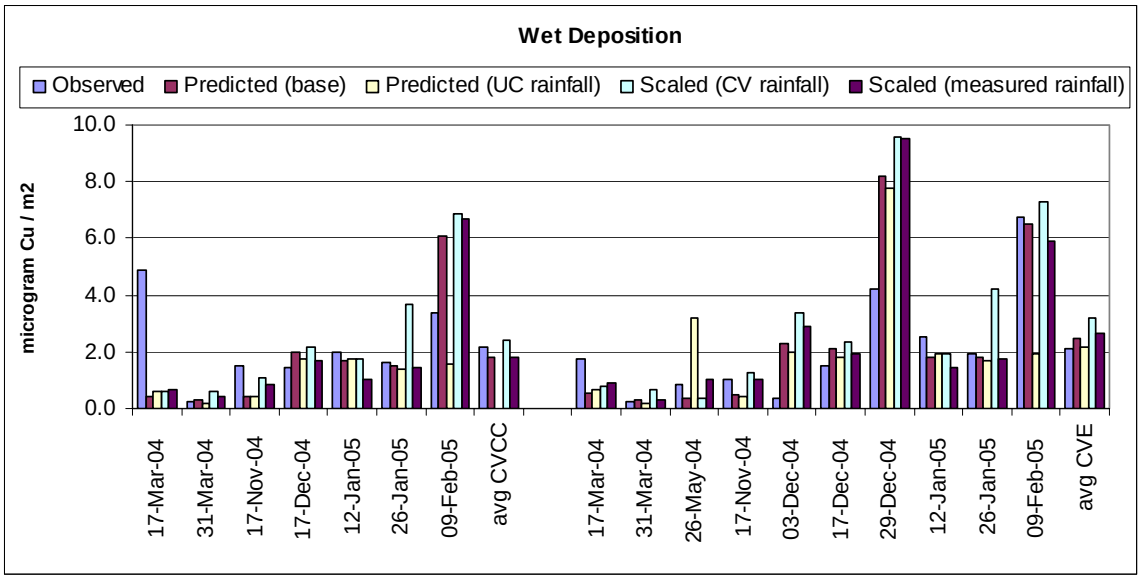

Figure 11. Comparison of Cu wet deposition fluxes: observed vs. predicted using Union City rainfall data (Run 4) vs. scaled using Bellingham Drive, Castro Valley data and data from wet deposition monitoring sites.

4.2.3 Spatial and temporal allocations of BPWD emissions

The sensitivities of the model predictions to spatial and temporal allocations were tested by using alternative methodologies to conduct the allocations. In Run 6, the local model's domain was enlarged to include another section of I580 as it turns NW East of the Castro Valley Creek subwatershed. An approximate amount of emissions was assumed to be equal to that of the I580 emissions within Castro Valley Creek subwatershed for this simulation. An equivalent amount of emissions was subtracted out of the regional domain.

The local contribution to wet deposition fluxes increased with an additional length of highway increased by 16% on average at CVCC and 8% at CVE. There was little change in the regional contribution of the wet deposition flux. As a result, there was a 3% increase in the predicted wet deposition fluxes at CVCC and a 2% increase at CVE. Thus, the effects were quite negligible on the wet deposition predictions.

For dry deposition, adding the extra length of highway increased the local contribution by 0.4 $\mu g/m^2$ for both CVE and CVCC. The impact of the added emissions was limited by the presence of hills between the added emission source and the receptors. Local contributions to the dry deposition fluxes at Madison increased by less than 0.1 $\mu g/m^2$, consistent with the limited reach of highway emissions. The Redwood site was

most impacted by the additional highway source, receiving an extra dry deposition flux of 0.9 $\mu g/m^2$. The reason for this increase may be Redwood's location along the path of the prevailing wind blowing from an extended portion of the highway. The regional component of dry deposition fluxes did not change significantly due to the redistribution of sources. Therefore, enlarging the domain of the local simulation to include more highway emissions had negligible effects on the predictions of wet and dry deposition fluxes of BPWD.

Because wet deposition fluxes were aggregated over two weeks, the increase in weekday emissions and decrees in weekend emissions had a very small effect on the average predictions (0.01 to 0.03 $\mu g/m^2$). Predictions of 6 samples changed by more than 10%, but not always in a direction towards the observations.

Applying a weekly profile also had no significant effect on the average predicted dry deposition flux at Madison, a 0.1 to 0.2 $\mu g/m^2$ change on the average prediction of dry deposition fluxes at CVE and CVCC, and a 0.7 $\mu g/m^2$ change at Redwood. Dry deposition measurements were aggregated for two days only, hence differences in predictions were more prominent in individual samples. At CVCC and CVE, the model generally underpredicted dry deposition fluxes. Therefore, an increase in local emissions during the week resulted in slight improvements in the performance of the predictions of the weekday dry deposition samples. A corresponding underprediction of weekend samples was simulated. The reverse was true for Redwood. Because of the general overprediction there, weekday measurements were overpredicted by even greater amounts, whereas predicted weekend dry deposition fluxes showed some improvements over the base case. The regional dry deposition flux was less affected than the local flux by the application of a weekly emission profile; hence only small changes were simulated at Madison, where the regional flux dominated over the local contribution.

In sum, the application of a weekly temporal profile to the emissions did little to alter the overall model performance.

4.2.4 Particle size

Based on the experiments conducted by Haselden et al. (2004), the mass median diameter was determined to be between 3.1 μm and 4.0 μm, with a nominal value of 3.5 μm. We used the lower value in the range and an alternative definition of the particle size distribution in a sensitivity study. Reducing particle size had the overall effect of increasing modeled wet deposition fluxes at the expense of dry deposition fluxes. Regional contributions to wet deposition fluxes (modeled using the mass median diameter) decreased, while local contributions increased due to the different responses for different size bins. The increased total predictions when the model already overpredicted (e.g., 3 December and 29 December for CVE) degraded model performance for wet deposition during those periods. Overall, model performance improved slightly for both CVE and CVCC.

Dry deposition fluxes decreased when particle sizes decreased in both the regional and local models. Larger relative decrease was simulated in the local contributions (30 to 70%, largest decrease at Madison, smallest decrease at Redwood) than the regional model (approximately 30% at all sites). As a result, the average dry deposition fluxes at Redwood and Madison were approximately 70% of the base case values. The predicted dry deposition fluxes at CVE and CVCC were 60% - 63% of the base case values in the particle size sensitivity run compared to the base run. While the predictions at Redwood improved in the sensitivity case, the corresponding degradation of model performance at CVE and CVCC provided no justification that the smaller particle size was a more realistic value.

4.2.5 Particle density

Particle density affects the dry deposition velocity of particles. Its effects on the wet deposition fluxes are indirect, through a change in the ambient concentrations of BPWD. Particle density was increased from 3 g/cm^3 to 5 g/cm^3. The regional contribution of wet deposition fluxes decreased by 7-8% at CVE and CVCC. The corresponding decrease of the local contribution was 2-3%. A 4% change in wet deposition fluxes resulted from the combination.

Dry deposition fluxes increased with particle density in both the regional and local models. On average, the dry deposition flux increased from 1.0 μg/m^2 to 1.4 μg/m^2 at Madison (compared to the observed value of 8.8 μg/m^2). This change was akin to the response of the regional model to increased density. At CVCC, the predicted dry deposition flux increased from 8.9 to 10.6 μg/m^2 (the sensitivity result was about 63% of the averaged observed value). At CVE, a similar increase was simulated, from 8.3 to 10.4 μg/m^2 (compared to the observed average flux of 14.5 μg/m^2). Despite a fairly strong sensitivity to the density parameter, the predictions at these residential area monitors remained below the observed values. Dry deposition fluxes increased also at the Redwood site, from 81 to 89 μg/m^2 when particle density was increased, resulting in a larger overprediction compared to the observed value of 29 μg/m^2.

4.2.6 Emissions

Based on the estimates of Rossolot, uncertainties in the emissions of BPWD were approximately 30%. Wet and dry deposition fluxes scaled almost linearly with emissions in the regional and local scale models. Therefore, increasing emissions by 30% increased the overpredictions of wet deposition events where the model already overpredicted, and resulted in an average overprediction at both CVCC and CVE sites.

For dry deposition fluxes, the increase in emissions resulted in corresponding increases in dry deposition fluxes at all sites. The resulting average dry deposition fluxes at Madison, CVCC, CVE, and Redwood were 1.3, 11.5, 10.8, 106 μg/m^2, respectively.

4.2.7 Re-emissions

Because the regional model accounted for re-emissions in the base case, this sensitivity study only affected the local model. Re-emissions served to redistribute air deposition from road surfaces to other areas of the Castro Valley Creek subwatershed. As a result of re-emissions, the net air deposition of BPWD on road surfaces would be zero. At the receptors, the wet and dry deposition terms increased slightly.

Wet deposition increased by 1% at CVE and 4% at CVCC. The increase resulted from an 8% increase in the local deposition fluxes at CVE and 13% at CVCC when re-emissions from local roads were taken into account.

The dry deposition fluxes increased by 3% at CVE and CVCC and 2% at Redwood. Summing local and regional contributions (which did not change from the base case), the increase in deposition fluxes were of the order of 2% at Redwood, CVE and CVCC. There was no change at the Madison site.

4.2.8 Summary

Model performance for wet deposition was quite satisfactory in the base case, with an average overprediction of 15% at CVE and an average underprediction of 18% at CVCC. Predicted wet deposition fluxes were composed of both regional and local influences, with the regional influence being quite important on average. While there was room for improvement in the prediction of individual wet deposition samples, it appeared that there was some variability in the ambient wet deposition fluxes that could not be captured by the model. Parametric uncertainties tested in the sensitivity studies tended to change the magnitude of the fluxes in general but did not improve individual predictions. Rainfall data uncertainties, while improving model performance for some periods, did not explain the largest overpredictions and underpredictions.

Dry deposition performance was less satisfactory. The models reproduced the relative magnitude of dry deposition fluxes, high nearest to I580, moderate at the residential sites at CVE and CVCC, and low at the higher elevation site at Madison. However, the modeled range of dry deposition fluxes was much higher than observed, resulting in a significant overprediction at Redwood and underpredictions at the other sites, especially at Madison. Predicted dry deposition fluxes were dominated by local influences at Redwood, CVCC, and CVE. Regional influences constituted a small percentage of the fluxes at these sites, but were the major contribution at Madison. Local influence, therefore, had limited range for dry deposition fluxes. Sensitivity studies showed that known uncertainties tended to change the overall magnitude in the same direction at all sites, rather than to reduce the site-to-site differences. The next section explores some possible limitations in the formulation of the air deposition models, including possible flaws in the data approaches.

4.3 Hypothetical investigations

This section explores a number of what-if scenarios beyond the data uncertainties that have been characterized by BPP researchers. The focus of these investigations was to determine if key assumptions about BPWD emissions, dispersion, and deposition may be flawed, especially in light of the models' inability to reproduce the relatively gentle gradient of the dry deposition fluxes between Redwood (next to I580) and Madison (upper watershed).

4.3.1 Sources of dry deposition at Madison

As shown in Section 4.2, predictions of dry deposition fluxes at Madison were almost an order of magnitude less than the observed values. As the model was set up in the base case and sensitivity cases, dry deposition fluxes at Madison were dominated by the regional influence. Therefore, the mismatch between model results and data may be caused by (1) underpredictions of dry deposition fluxes originating from regional sources or (2) lack of local influences predicted by the models, or a combination of the two factors.

Hypothesis: Regional influence dominated the dry deposition fluxes at Madison and was underpredicted by the regional model. Any increase in the predicted regional influence would affect all sites equally; hence such an increase would also improve the model performance for the prediction of dry deposition fluxes at CVCC and CVE, but not Redwood. The average observed dry deposition flux at Madison was 8.8 $\mu g/m^2$/day or 0.37 $\mu g/m^2$/hour. The average emissions rate of Cu in the regional watershed was 5.35 kg/hour (6% x 2142 kg/day) for BPWD plus a small amount of industrial air emissions. The regional emissions were distributed over an area of 8,913,383,406 m^2 in the watershed, resulting in a density of 0.60 $\mu g/m^2$/hour. Comparing the emission rate and the deposition rate based on this hypothesis, a substantial portion (61%) of the Cu emissions needed to deposit within the Bay Area. Given an average wind speed of 11.2 km/hour (3.1 m/s), 61% of the Cu would need to deposit in 8 hours before the wind parcel traversed the bay area watershed. Dry deposition is modeled as an exponential decay function

$$\frac{C_{final}}{C_{initial}} = \exp\left(\frac{-V_d t}{H}\right) \tag{5}$$

Using an average mixing height (H) of 686 m during March 2004 to February 2005, a time period (t) of 8 hours, and 0.39 as the ratio $C_{final}/C_{initial}$, the deposition velocity (V_d) would need to be approximately 2 cm/s. This dry deposition velocity is consistent with particles that are larger (e.g., > 10 μm in diameter) or that have a higher density (e.g., > 10 g/cm^3) and inconsistent with current knowledge about BPWD. The nominal BPWD particle is 3.5 μm in diameter and has a density of 3 g/cm^3. A typical deposition velocity associated with the BPWD is 0.1 cm/s.

A fraction (9%) of the BPWD is associated with diameter of > 10 μm. For this fraction to be responsible for a regional deposition rate of 8.8 $\mu g/m^2$/day, total BPWD emissions would need to be about 10 times higher than the current estimate, which seemed unlikely given that the emission estimates are only uncertain by a factor of 1.4 (95% intervals; Rossolot, 2005a).

Given current knowledge of BPWD emissions and BPWD particle characteristics, it would be unlikely for the regional contribution of BPWD at Madison to explain the entirety of the underpredictions of dry deposition at that site.

Hypothesis: Local non-highway influence on dry deposition fluxes was underrepresented in the model, especially lacking at Madison. The highway-only simulation indicated that highway emissions contributed only a small amount to the simulated dry deposition fluxes at CVE, CVCC, and negligibly at Madison.

Ideally, a detailed representation of surface street sources would require at the very least the location and width of probably hundreds of individual street segments. In addition, traffic data on each segment of the street would also be needed to properly apportion emissions. The data requirements for such an approach were incompatible with the data resources available to this project. As a compromise, surface street sources were represented by area sources in the Castro Valley Creek subwatershed. There are obvious limitations to this approach. First, areas with high and low road/traffic density receive the same emissions input per m^2. Second, since emissions are spread out over road and non-road surfaces, the density (kg/m^2) of emissions would be lower than actual on-road values. Third, because uniform distribution was assumed, any effects on the monitored fluxes due to the distance from road would be obscured.

In the base case simulation, we visually inspected a Castro Valley street map and located the area with the highest density of streets over which an area source was placed. The area did not include the panhandle part of the watershed where the Madison site was located. Given the limited range of influence of local sources, it was likely that the lack of local influence simulated in the base case was related to the placement of the area sources. Therefore, we ran a simulation (Run 10) where the surface emissions were redistributed to include areas higher up in the watershed without a dense network of roads. To maintain a consistent total surface street emission in the Castro Valley Creek subwatershed, the area source emission density decreased by 6% in this run due to the increase in the area. Average dry deposition fluxes at 4 sites are presented in Figure 12. Including the panhandle area for surface street emissions substantially improved the dry deposition fluxes predicted at Madison without changing the predictions at CVE, CVCC, and Redwood. This simulation showed the sensitivity of the modeled dry deposition fluxes to the distribution of local emissions from surface streets. In addition, the similarities between the predicted values at CVE, CVCC, and Madison in the larger-area simulation highlighted the effects of using the same emissions input for areas with higher (e.g., CVE) and relatively low (e.g., Madison) traffic activity.

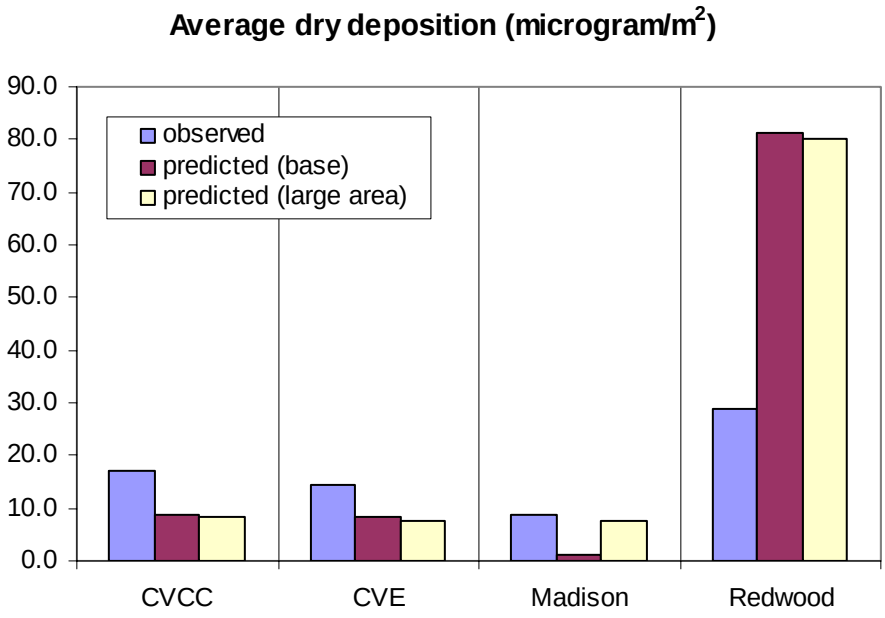

Figure 12. Observed and predicted Cu dry deposition fluxes in base and area source runs at CVCC, CVE, Madison, and Redwood.

4.3.2 Possible reasons for underpredictions of dry deposition fluxes at CVE and CVCC

Based on the presence of larger roads near Castro Valley downtown, it does not seem unreasonable that emissions per area would be higher at the lower part of the watershed compared to the higher part of the watershed. A simulation was performed to understand the sensitivity of dry deposition predictions to surface street emissions by doubling the surface street emissions (Run 11), excluding the panhandle area. As expected, the predicted dry deposition fluxes at CVE and CVCC increased by 80% to 90% and the results at Redwood road increased by 10%. Therefore, it seems possible that the observed gradient in the wet deposition fluxes between CVCC and CVE on one hand and Madison on the other is due to the strength of emissions on the nearby surface streets. The underprediction of CVE and CVCC may be corrected if surface street emissions could be re-distributed by VMT, number of stops, or other measures of traffic activity (e.g., number of lanes or speed limits). Unfortunately, such traffic activity data were not available within the scope of this project.

4.3.3 Overpredictions of dry deposition fluxes at Redwood

The dry deposition fluxes at Redwood were dominated by emissions from I580. The Redwood site was located within 50 m of I580. The monitor was located below I580, despite being on a commercial building. That section of I580 is lined with a sound wall. It is possible that the sound wall blocks the path of a portion of the BPWD

emissions and prevented it from reaching the Redwood building on the other side. ISC-ST, the local model employed in this work, does not have the capability to model an obstacle between a source and a receptor. The apparent effect of such a blockage would be (1) an apparent release height that is higher than the actual road surface, and (2) a reduced source strength as experienced by a receptor on the other side.

Typical sound walls are approximately 10 to 16 ft high. Elevating I580 by 6 m (upper limit of the sound wall height) (Run 12) had almost no effect on the dry deposition predictions at Redwood. In fact, it took elevating the highway by 30 m in a hypothetical scenario to reduce the average dry deposition flux at Redwood by 50% from the base case value of 81 $\mu g/m^2$ (the average observed flux was 28.9 $\mu g/m^2$). Obviously, the presence of the sound wall cannot be approximated by simply increasing the release height of the highway source.

An average concentration profile in the vertical direction at the sound wall was calculated using emissions from the appropriate section of I580. Based on this profile, 75 % of the emitted BPWD could have been blocked by a 10-ft sound wall. Therefore, the presence of the sound wall was expected to decrease concentrations by 0% to 75%. The lower limit corresponded to the case where particles running into the sound wall were reflected, but no mass was lost (all material eventually escaped after an infinite number of bounces). The upper estimate corresponded to the case where all the blocked material became immobilized on the sound wall. The observed flux corresponded to 36% of the predicted dry deposition at Redwood. Therefore, the model's inability to model the sound wall may well have some effects on the model performance at the Redwood site, where dry deposition was apparently dominated by the nearby highway source.

Overpredictions at the Redwood site would reduce in a scenario where BPWD emissions were reduced on highway I580. The current base case emissions estimates were based on the application of a BPWD emission factor to VMT on different roads. Because less braking occurs on the highway than on surface streets (surface streets have traffic lights and stop signs), it does not seem unreasonable to envision a scenario where the BPWD emission factor (emissions per VMT) is lower on highway than on surface streets. Using the results of the base case and Run 9, the dry deposition fluxes were estimated in a scenario where highway emissions are reduced by 50% and surface street emissions were allocated as in the base case. Overpredictions at the Redwood site was much reduced without significant affects on the predictions at the CVCC, CVE, and Madison sites (see Figure 13).

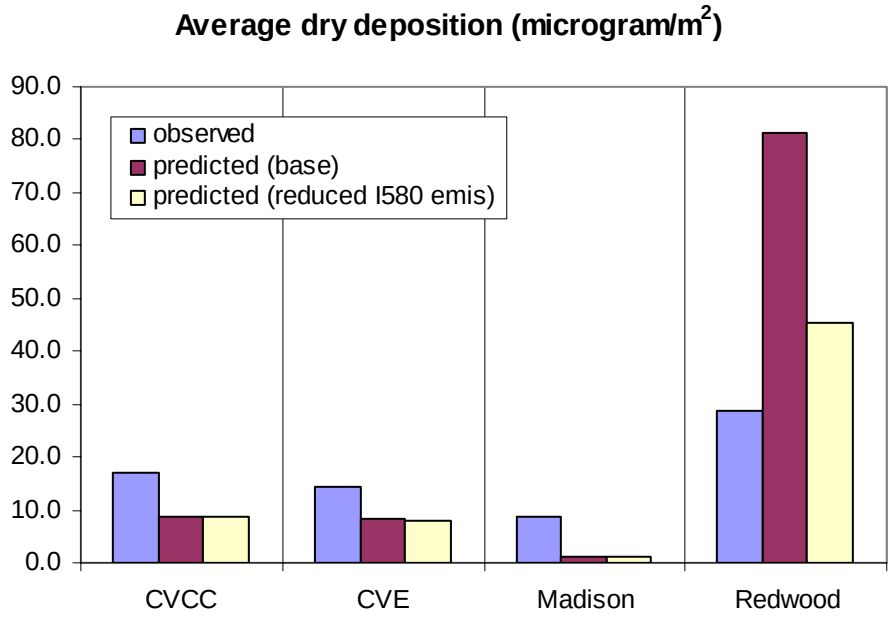

Figure 13. Observed and predicted Cu dry deposition fluxes in base and reduced highway emission scenario at CVCC, CVE, Madison, and Redwood

4.3.4 Remarks

Another possible reason for the local model to predict a higher-than-observed gradient of dry deposition fluxes may be related to mis-predictions in the deposition velocities (Equations 2) from meteorological input data. If dry deposition velocities were overpredicted, they could cause large overproductions of dry deposition fluxes (Equation 1) near source, resulting in a too-rapid depletion of air concentrations and a subsequent underprediction of the dry deposition fluxes farther away. Possible flaws in the deposition model formulation, especially the regulatory model ISC-ST3, could not be investigated here.

4.4 Best estimate

Except for some variability in the wet deposition fluxes that was not represented by the model predictions, wet deposition fluxes from the base case compared reasonably well with the monitoring data and no adjustment to the simulation was proposed based on those data.

Some limitations were identified in the modeling of dry deposition fluxes, but none of the uncertainties in the input data universally improved model performance at all sites. Not implemented in the best estimate case were changes that could potentially improve model performance but were unsubstantiated by the data-compilation process undertaken by BPP. The hypothetical investigations indicated that the dry deposition results from the local model would improve in a scenario where BPWD emissions were (1) reduced on highway I580, (2) increased on the surface streets (especially those located in the lower watershed), and (3) included in the upper watershed. The current base case emissions estimates were based on the application of a BPWD emission factor to VMT on different roads. Because less braking occurs on the highway than on surface streets (surface streets have traffic lights and stop signs), it does not seem unreasonable to envision a scenario where the BPWD emissions per VMT is lower on highway than on surface streets. Guidance from BPP would be needed to design a suitable data strategy and simulation to address this possibility.

For a more realistic scenario, re-emissions were taken into account from all road surfaces. The base case formulation was retained for the final simulation with the exception that surface emissions were allocated to the panhandle area.

A five year simulation will be conducted using receptors to be designated by the watershed and bay modelers. Wet and dry deposition fluxes will be estimated on a daily basis for those receptors.

5. Conclusions

Wet and dry deposition fluxes of Cu from airborne BPWD emissions and industrial sources were estimated using a regional model and a local model. Model performance for wet deposition fluxes was generally acceptable when compared to the observations at CVE and CVCC. Wet deposition fluxes in the Castro Valley Creek subwatershed were predicted to contain both regional and local components, with the regional contribution being more significant than the local contribution during most monitoring periods.

Dry deposition predictions were dominated by fluxes originating from local sources. The model performance was less satisfactory. The model overpredicted dry deposition fluxes at the Redwood site, which was located in close proximity to the major BPWD source in Castro Valley Creek subwatershed. Dry deposition fluxes at the mid and upper watershed sites were underpredicted. The gradient of the dry deposition fluxes from low to high watershed depended upon the gradient of the source strengths of the highway vs. area sources. Refinements in the highway vs. surface emission factors (lower on highways, higher on surface streets on a per VMT basis) may improve the estimates of dry deposition fluxes. One surface street emission density was used for the entire Castro Valley Creek subwatershed. However, we believe that the model performance on dry deposition could be improved if activity-based allocation could be used for surface streets, e.g., high traffic density roads at the lower watershed should receive higher area emission rates. Regional background could not explain the observed dry deposition fluxes at the Madison site, but representing roads within the mountain ridge development led to improved predictions compared to the observed value. The accuracy of the predicted dry deposition fluxes was limited by the inability of the model to represent a barrier (sound wall) to the transport of BPWD from I580 to the nearby Redwood site and by the lack of detail in the modeling of surface street emissions. Uncertainties in the model representation of dry deposition were not investigated within the present scope.

Model predictions were most sensitive to the amount of Cu estimated to be present in BPWD (± 67% in the predicted wet and dry fluxes). The next most influential piece of data was the emission rates of BPWD (25-35% in wet and dry fluxes for individual periods in response to a 30% change in emissions).

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