Modeling the Contribution of Copper from Brake Wear Debris to the San Francisco Bay Phase 2

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EXECUTIVE SUMMARY

Reducing levels of copper in runoff in order to reduce harmful environmental impacts has become important throughout California. The Brake Pad Partnership has conducted a series of interconnected technical studies to determine whether or not copper from brake pads contributes significantly to copper in surface waters in the San Francisco Bay watershed. As part of the Partnership's studies, air deposition modeling (Pun et al, 2006), watershed modeling (Donigian and Bicknell, 2007), and bay modeling (URS, 2007) were conducted. Each of these models used information about the quantity of copper being released into the environment from both natural and human sources, which range from anti-fouling coatings on boats to brake pads (Rosselot, 2006 and Rosselot, 2007).

The Partnership's technical studies showed that brake pad wear debris is a significant contributor to copper in runoff to the San Francisco Bay, particularly in highly urbanized sub-watersheds. While work done by the Partnership used the San Francisco Bay area as an example, many of the study results have broad implications.

AQUA TERRA Consultants performed the watershed modeling portion of the technical studies, using the U.S. EPA's Hydrological Simulation Program-FORTRAN (HSPF) model to estimate the copper in runoff to the bay. In the Phase 1 modeling effort, three cases of copper release (flux) scenarios were modeled, one called brakes-high, one called brakes-low, and one called median estimate. These three scenarios were selected because results based on them adequately represented the range of the relative contribution of copper released from brakes, and because they take the uncertainty in the estimates of both brake and non-brake releases into account. Each scenario was modeled with and without the brake source terms in order to get an estimate of the relative contribution of copper from brakes. Based on the modeling, the total load of copper in runoff to the bay was estimated to be 56,000 kg/y, and the contribution of copper from brake pads to the total copper load in runoff to the bay is from 10% (for the brakes-low case) to 35% (for the brakes-high case).

The watershed modeling effort of this report is a follow-on effort to the Phase 1 modeling, and this report is a companion piece to the report for the Phase 1 modeling. This follow-on effort (Phase 2) was done to better understand the full extent of the contribution of copper from brakes on copper in runoff, and determine the timeframe over which reductions in copper from brakes will result in reductions of copper in surface waters. The Phase 2 modeling was conducted using the same model set-up and modeling software as the Phase 1 study documented by Donigian and Bicknell (2007).

Effects of Phase 1 Modeling Buildup/Washoff Techniques and Parameters on Estimated Copper Loads:

It has been observed that when materials are deposited to impervious surfaces, they do not continuously accumulate. Instead, the rate of buildup of the materials asymptotically approaches a maximum. The maximum is reached when processes that remove the material from the surface are removing material at the same rate at which they are deposited onto the impervious surface. The buildup/washoff modeling technique used in the Phase 1 watershed modeling effort incorporates the standard buildup and washoff function in HSPF, which is also used in most urban stormwater models, to account for the observed asymptotic approach towards a maximum copper storage on impervious surfaces. Once copper buildup reaches the maximum, any more deposited material is treated as if it never occurred, when in fact the material is being transported, and/or dispersed, from the impervious surface to adjacent surfaces. Much of the first part of this follow-on modeling effort was conducted in order to find out how large an underestimate of the relative contribution of brake pad copper to total urban anthropogenic copper loads was created by the buildup and washoff functions in the Phase 1 modeling.

The first task in this part of the follow-on effort was to conduct a brief literature review to investigate the fate of metals subsequent to deposition on roadways. The literature review concluded that copper disperses from roadways and reaches a background level (the level observed in areas that are not affected by roadway copper) within approximately 10 meters, sometimes within as little as 5 meters to 6 meters.

Based on this conclusion, the HSPF buildup-washoff model was reviewed, and the modeling technique was modified to better account for the copper that is “lost” from the standard modeling technique. This modified model was tested on several sub-watersheds, which were selected to provide a range of conditions – geographic, soils, meteorological – across the Bay Area, and a range in terms of contributions of copper from brake pad wear debris. The modified modeling technique was based on capturing the copper that is lost from the Phase 1 technique for handling buildup/washoff on roadways, and transferring that copper to a roadside buffer area, where it is subject to washoff to surface waters. Mean annual loads to the Bay increased from 0.5-3.5% over Phase 1 loads when the buffer area was assumed to be pervious, and 15-30% when impervious.

Table ES1 shows the relative contribution of copper from brake pads (as opposed to the contribution from sediment and the contribution from non-brake pad anthropogenic sources of copper) to total loads of copper to the San Francisco Bay under three scenarios. The first scenario is the Phase 1 model results, where the copper removed by the model’s buildup and washoff function is unaccounted for. The second and third scenarios apply this “lost” copper to roadway-adjacent buffer that is assumed to be either 100% pervious or 100% impervious. The roadway-adjacent buffer is known to be a mix of pervious and impervious surfaces, so the second and third scenarios represent the potential range of the relative contribution of copper from brake pads when copper removed by the model’s buildup and washoff function is accounted for. The Peninsula Central and the Upper Colma sub-watersheds have the highest estimated relative contribution of copper from brake pads in the San Francisco Bay watershed, and the relative contribution of copper from brake pads in these sub-watersheds increases from 49% and 50%, respectively, to somewhere between 50% and 60% when copper removed by the model’s buildup and washoff functions is accounted for. Table ES1 shows that the Phase 1 modeling’s buildup and washoff techniques slightly underestimated the relative contribution of brake pad copper in watersheds where the roadway-adjacent buffer is largely pervious; modeling copper accumulation on these pervious buffer surfaces suffers from the same unaccounted for copper as was seen in Phase 1. As the imperviousness of the roadway-adjacent buffer increases, the significance of the copper “lost” in the buildup and washoff function increases.

Table ES1. Effect on the Relative Contribution of Brake Pad Wear Debris Copper to Total Copper Loads of Applying Copper "Lost" in the Buildup and Washoff Functions to Roadway-Adjacent Buffer

Sub-Watershed (% impervious)	Relative Contribution of Copper from Brake Pads (% of total load of copper)		
	Phase 1 Modeling (Median Estimate Case)	100% Pervious Buffer, Phase 2 Modeling	100% Impervious Buffer, Phase 2 Modeling
East Bay North (37%)	36%	38%	44%
Peninsula Central (16%)	49%	50%	60%
Petaluma (0.2%)	7%	8%	22%
Santa Clara Valley Central (6%)	28%	30%	45%
Upper Colma (27%)	50%	52%	60%

Table ES2 answers the question ***"How large is the Phase 1 modeling's buildup and washoff function-associated underestimate of the relative contribution of brake pad wear debris copper to total anthropogenic copper loads?"*** These results suggest that the relative contribution of copper from brake pads to all anthropogenic sources of copper was underestimated by the buildup and washoff functions in the Phase I modeling work by as little as 2% in the most rural sub-watersheds (e.g. Petaluma) to no more than 9% in the most urbanized sub-watersheds (e.g. East Bay North). In the urbanized Upper Colma sub-watershed, the contribution of copper from brake pad wear debris to anthropogenic sources of copper in runoff is between 58% and 66%.

Table ES2. Effect on the Relative Contribution of Brake Pad Wear Debris Copper to Anthropogenic Copper Loads of Applying Copper "Lost" in the Buildup and Washoff Functions to Roadway-Adjacent Buffer

Sub-Watershed (% impervious)	Relative Contribution of Copper from Brake Pads (% of anthropogenic load of copper)		
	Phase 1 Modeling (Median Estimate Case)	100% Pervious Buffer, Phase 2 Modeling	100% Impervious Buffer, Phase 2 Modeling
East Bay North (37%)	41%	43%	50%
Peninsula Central (16%)	54%	54%	65%
Petaluma (0.2%)	31%	33%	63%
Santa Clara Valley Central (6%)	45%	47%	63%
Upper Colma (27%)	57%	58%	66%

Sensitivity analysis was performed for the accumulation maximum and the copper exchange rates in streambed sediment to evaluate the effect of uncertainty in these key model parameters. The testing was primarily evaluated by comparing the predicted copper loads to the Bay with the loads from the Phase 1 effort. Loads changed significantly when the accumulation limit was modified, as expected. At one-half the values used in the Phase 1 modeling, the load changes for the example sub-watersheds ranged from -5% to -40%, and at 2 times the values used in the Phase 1 modeling, the load changes ranged from +7% to +37%. Varying the copper exchange rates in the bed sediment showed a much smaller effect, with changes in loadings ranging from -0.5% to +3%.

The final investigation in this part of the Phase 2 modeling examined what the effect of channelizing the reaches in the Upper Colma sub-watershed would be. The results of this indicate that copper levels in the stream bed sediments can become effectively saturated after many years of high copper loading, and subsequently start to behave like channelized stream courses where little adsorption to stream bed sediment is possible. For natural streams, the saturation of the bed inhibits copper exchange, whereas for channelized streams the lack of bed sediment is the limiting factor in the exchange process. Thus, the modeling showed relatively small differences in these two conditions but for different reasons.

Timescale for Environmental Response to Reductions in Copper from Brake Pad Wear Debris:

The second portion of the Phase 2 modeling was conducted in order to help understand the length of time it will take for brake pad wear debris copper to wash out of California's urban watersheds. The effects of reducing brake-related sources were investigated by turning off brake copper sources at the beginning of a 25-year simulation, and evaluating the time until brake copper loads to surface waters are reduced to 5%, 10% and 20% of the loads that would have occurred had brake sources of copper remained unchanged in each modeled sub-watershed. These levels correspond to 95%, 90%, and 80% reductions in loads from brakes, respectively.

Table ES3 shows that copper loads reach 20% of brake debris loads, or an 80% reduction, within 5 years in four of the five example sub-watersheds, and between 6 and 10 years in the other sub-watershed. To attain a 95% reduction, close to a decade (i.e., 6 – 10 years) was needed for three of the sub-watersheds, more than a decade (11 – 15 years) for one sub-watershed, and more than two decades for the other sub-watershed). Two watershed characteristics that appear to affect these results are the length of the stream channel and, to a lesser degree, the extent of urbanization (and higher releases of copper from brake pad wear debris). Longer streams and higher copper deposition resulted in longer time lags.

The lag time for brake source reductions was also evaluated under both long-term dry and long-term wet meteorological conditions. Table ES3 shows that meteorological conditions had a relatively minor impact on the results, with the 'dry' scenarios producing slightly longer time lags and the 'wet' scenarios producing shorter ones.

The East Bay North, Peninsula Central, and Upper Colma sub-watersheds represent a range of urbanized San Francisco Bay area sub-watersheds that were investigated in the Phase 2 modeling. Thus, the answer to the question ***"How long will it take copper from brake pad wear debris to wash out of California's urban watersheds?"*** is that it will take from 0 to 5 years for 80% and from 6 to 15 years for 95% of reductions in releases of copper from brake pad wear debris to be realized in urban surface waters in the San Francisco Bay area.

Table ES3. Time Lag Required to Reach 20% and 5% of the Brake Copper Loads Observed When Brake Sources Are Unchanged (Years)

	Time Lag to Reach 20% of Baseline Copper Loads (years), 80% Reduction in Brake-Derived Loads		
	Historical Meteorological Data, Water Year 1981-Water Year 2005	Dry Scenario, Water Year 1984 - Water Year 1994	Wet Scenario, Water Year 1995 - Water Year 2005
East Bay North	0 - 5	0 - 5	0 - 5
Peninsula Central	0 - 5	0 - 5	0 - 5
Petaluma	0 - 5	0 - 5	0 - 5
Santa Clara Valley Central	6 - 10	6 - 10	6 - 10
Upper Colma	0 - 5	0 - 5	0 - 5

	Time Lag to Reach 5% of Base/Background Cu Loads (years), 95% Reduction in Brake-Derived Loads		
	Historical Met Data, WY84-WY05	Dry Scenario, WY84-WY94	Wet Scenario, WY95-WY05
East Bay North	6 - 10	6 - 10	6 - 10
Peninsula Central	6 - 10	10 - 15	6 - 10
Petaluma	6 - 10	6 - 10	0 - 5
Santa Clara Valley Central	>20	>25	16 - 20
Upper Colma	11 - 15	11 - 15	11 - 15

SECTION 1.0

INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES

The Brake Pad Partnership is a multi-stakeholder effort involving brake pad manufacturers, stormwater managers, water quality regulators, and environmental groups. To achieve effective reductions of copper from brakes in stormwater discharges, the Partnership is translating its findings into control measures that would ensure reductions in copper from brakes entering stormwater runoff.

The Brake Pad Partnership has conducted a series of interconnected technical studies to determine whether or not copper from brake pads contributes significantly to copper in surface waters in the San Francisco Bay watershed. As part of these studies, air deposition modeling (Pun et al, 2006), watershed modeling (Donigian and Bicknell, 2007), and bay modeling (URS, 2007) were conducted. Each of these models used information about the quantity of copper being released into the environment from both natural and/or human sources (Rosselot, 2006 and Rosselot, 2007).

Human sources of copper released to the environment range from anti-fouling coatings on boats to brake pads. Estimates of the releases of copper from brake lining wear were made by developing emission factors based on vehicle distance traveled. Air emission factors were created first, using several independent methodologies, and the most appropriate methodology was selected for preparing the estimates of copper releases. Emission factors for releases to roadway were based on the air emission factors coupled with brake wear partitioning information.

Methodologies for estimating non-brake sources of copper depended on the type of source. Estimates were prepared for architectural copper, copper in pesticides (including pesticides applied to land in urban areas, agricultural land applications of pesticides, algaecide treatment of surface waters, pressure-treated wood preservatives, antifouling coatings on boats, and pool, spa, and fountain algaecides), copper in fertilizer, copper releases from industrial facilities (including releases in runoff), and copper in domestic water discharged to storm drains.

The inventory found that an estimated 240,000 kg (540,000 lb) of copper were released due to human activity in the San Francisco Bay watershed in 2003. Of this amount, 87,000 kg (36%) was copper released from brakes, nearly all of which is from brake pads on passenger cars. About half of the estimated copper released is released directly to pervious land surfaces where it is less likely to become entrained in runoff and reach bay waters. Copper in pesticides applied to urban land is the single largest source of copper releases to the environment in the San Francisco Bay watershed, with 100,000 kg released in 2003. This is 42% of the total human sources of copper released in the Bay area.

Estimates of the air deposition of copper, which are primarily due to brake pad wear debris, were modeled for the Brake Pad Partnership to provide information needed in the watershed and bay modeling efforts. Much of the brake pad wear debris that is emitted is emitted as very small particles that remain airborne for long periods of time before they undergo deposition. The watershed modeling also relied on water quality monitoring that was performed for the Brake Pad Partnership by the San Francisco Estuary Institute.

AQUA TERRA Consultants used the U.S. EPA's Hydrological Simulation Program-FORTRAN (HSPF) model (Bicknell et al., 2005) to estimate the copper in runoff to the bay. This Phase 1 study, whose purpose was to quantify the relative contribution that brake pads have on total copper in runoff to the San Francisco Bay, rather than the absolute amount of copper contained in runoff, is described briefly below in order to provide some context for the modeling described in this report.

For Phase 1, limited calibration runs were performed for Castro Valley Creek to determine selected copper washoff parameters, which were then adjusted and applied to all 22 of the modeled sub-watersheds within the Bay watershed. Consistency and quality assurance checks on as many sites/stations as possible with readily available data were performed. Model results were processed for flow, sediment and copper loads; annual and mean annual loads were tabulated; and daily flows and concentrations (both sediment and copper, total and dissolved) were reviewed as a quality assurance confirmation.

Each sub-watershed was modeled for water years 1981 through water year 2005; this ensured that an appropriate range of weather conditions was modeled. Land use types in the modeling were categorized as developed pervious, impervious, agricultural, shrub and wooded, grassland and wetland, and forest. Copper emissions were treated as if they were applied evenly across the appropriate land use category for each sub-watershed and were uniform over time except for wet deposition of copper, architectural releases of copper, and copper in industrial runoff, which are treated as rain-dependent. Brake wear debris released direct to roadways was modeled as applied to impervious surfaces, while non-brake releases were modeled as going straight to storm drains, to agricultural land, or to developed land, depending on the type of release.

Three cases of copper release (flux) scenarios were modeled, one called brakes-high, one called brakes-low, and one called median estimate. These three scenarios were selected because results based on them adequately represented the range of the relative contribution of copper released from brakes, and because they take the uncertainty in the estimates of both brake and non-brake releases into account. Each scenario was modeled with and without the brake source terms in order to get an estimate of the relative contribution of copper from brakes.

Based on the modeling, the total load of copper in runoff to the Bay was estimated to be 56,000 kg/y, and the contribution of copper from brake pads to the total copper load in runoff to the bay is from 10% (for the brakes-low case) to 35% (for the brakes-high case). Not surprisingly, the contribution of copper in runoff due to brake pads was found to be higher in urbanized sub-watersheds than in rural sub-watersheds. For example, for the median estimate case in the individual sub-watersheds, the contribution of copper from brake pads to the copper load in runoff varies from more than half in highly urbanized sub-watersheds to 15% for the rural sub-watersheds. Of the six sub-watersheds that contribute the greatest copper load to the Bay, some had their largest contribution from sediment, some from brakes, and some from non-brake anthropogenic sources.

In order to more fully understand the impact of any control measures on copper concentrations in runoff, the Partnership proposed that further watershed modeling be conducted in order to better understand the full extent of the contribution of copper from brake pads on copper in runoff, and determine the timeframe over which reductions in copper from brake pad sources will result in reductions of copper in surface waters. The methodology for this effort involves performing the additional model runs and analyses of selected sub-watersheds, using the Phase 1 model as a basis, and comparing results with the Phase 1 annual copper loads to the Bay. Figure 1.1 shows the 22 Bay Area sub-watersheds, and the five sub-watersheds selected for the Phase 2 modeling. They are East Bay North, Peninsula Central, Petaluma, Santa Clara Valley Central, and Upper Colma.

The example sub-watersheds were selected to provide a range of conditions – geographic, soils, meteorological – across the Bay Area, and a range in terms of brake contributions. Figure 1.2 shows the Phase 1 model results, and the five selected example sub-watersheds are identified in black boxes. These five sub-watersheds demonstrated a wide range in brake debris, anthropogenic non-brake, and sediment sources of copper, and thus were deemed to provide a broad spectrum of conditions for this assessment.

1.2 THIS REPORT

This report documents the results of this follow-on watershed modeling effort to better understand the buildup/washoff modeling techniques and how they affect the relative amount of brake-derived copper loading to surface waters; and the effects of brake source reductions on the time until copper loads approach levels that would occur in the absence of any brake sources. Section 2 documents the review of the buildup/washoff modeling techniques, including a literature review of the fate of metals deposited on roadways, analysis of the effects of adjusting the modeling techniquesto better represent copper deposited on roadways, and sensitivity of selected model inputs. Section 3 describes the analysis of the effects of brake source reductions on the timing of load reductions to surface waters. It includes a review of the metric for evaluating the reductions, and describes the model simulations and results under historical, long-term wet, and long-term dry meteorological conditions. Section 4 provides study conclusions, and Section 5 provides recommendations for further model analyses, modeling approach improvements, and additional modeling studies to complement and further refine the copper load estimate results provided through this work.

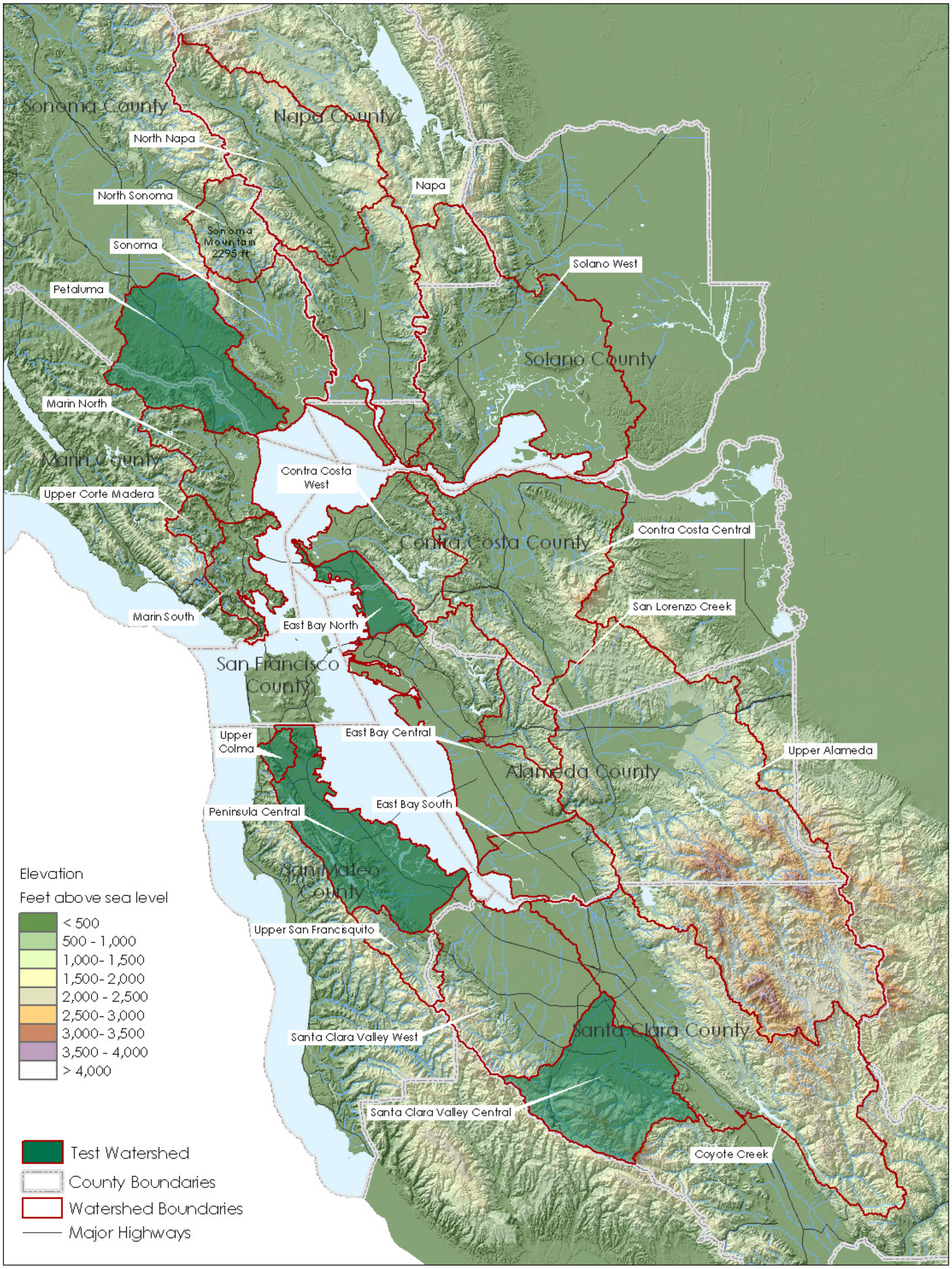

Figure 1.1 San Francisco Bay Study Area and Brake Pad Partnership Modeled Sub-Watersheds

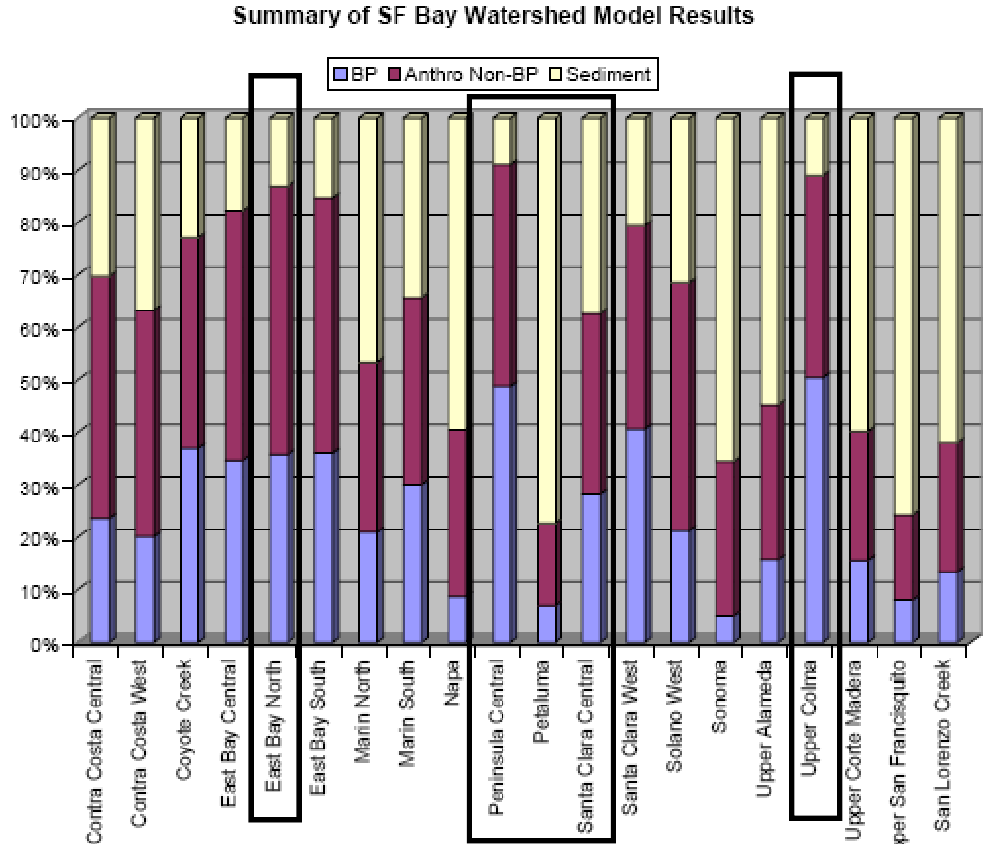

Figure 1.2 Phase 1 Model Results and Selected Example Sub-Watersheds

SECTION 2.0

EFFECTS OF BUILDUP/WASHOFF MODELING TECHNIQUES ON COPPER LOADING

It has been observed that when materials are deposited to impervious surfaces, they do not continuously accumulate. Instead, the rate of buildup of the materials asymptotically approaches a maximum. The maximum is reached when processes that remove the material from the surface are removing material at the same rate at which they are applied to the impervious surface. The Phase 1 watershed model incorporates a buildup and washoff function to account for the observed asymptotic approach towards a maximum for materials depositing on impervious surfaces (for example, releases to roadway of copper in brake pad wear debris). Once material buildup reached a maximum, any additional deposited material is treated as if it never occurred, when in fact the material is being transported and dispersed from the impervious surface to adjacent surfaces. This function is illustrated in Figure 2.1, where the removed or lost copper at any time is shown as the difference between the yellow line (representing the modeling of the Phase 1 study) and the red line. The yellow line is the actual amount of copper on the land, and the red line is the accumulation rate that would have occurred without the removal or loss mechanism. Due to this modeling technique, which is a standard approach in urban modeling (e.g. see Huber et al., 2006), there is concern that the previously (Phase 1) modeled values for copper loads to surface waters may underestimate the actual contribution of copper in runoff due to brakes.

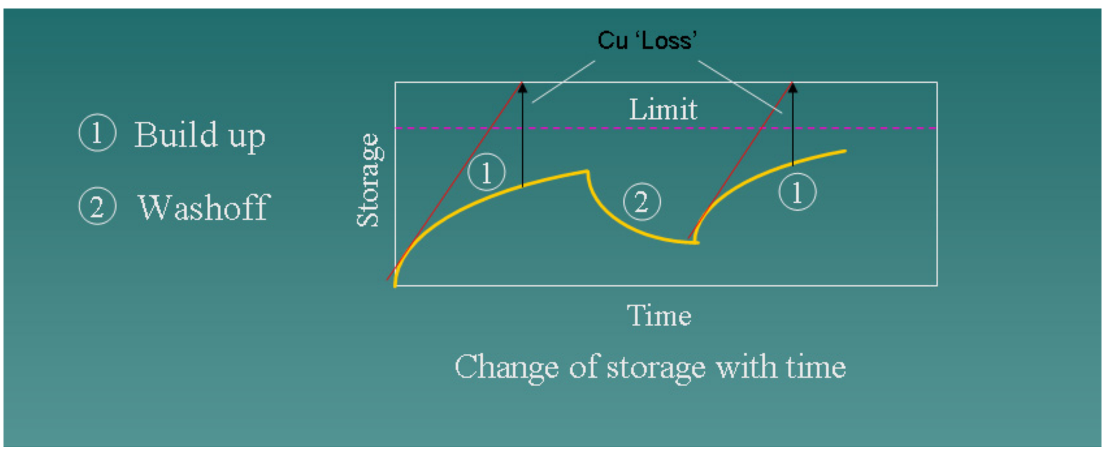

Figure 2.1 Copper Losses Due to Buildup-Washoff Approach

In order to better understand this issue, and guide the modeling and analysis, a literature review was conducted of metal (and specifically copper) behavior subsequent to deposition on roadways by motor vehicle traffic.

2.1 LITERATURE REVIEW

2.1.1 Introduction

Copper settles on roadways from sources including brake pad wear debris and air releases of copper. The majority of this copper is flushed away during storm events, polluting detention ponds, lakes, streams, and bays. However, what happens to the copper between events? Does it continue to build up on roadway surfaces or does it asymptotically approach some limit? If the second is the case, where is all of the copper going? In order to properly code the models, information relating to copper transport from road surfaces between storm events is needed for mass balance calculations. A few studies have been done to help resolve such issues.

2.1.2 Studies

In one study in Los Angeles, three sites (Figure 2.2) running along a road perpendicular to a major highway (I-405) were tested for copper concentration. This sampling site was chosen because wind generally comes off the Pacific Ocean and blows parallel to Constitution, the road the samples were taken from. The average traffic for I-405 is 300,000 vehicles/day. LA's climate is similar to that of the Bay Area as it is also a semi-arid climate with little rainfall in the summer months (see Figures 2.17 and 2.18). Samples were taken at 10, 150, and 450 meters downwind of I-405 along Constitution Avenue (Sabin et al., 2006).

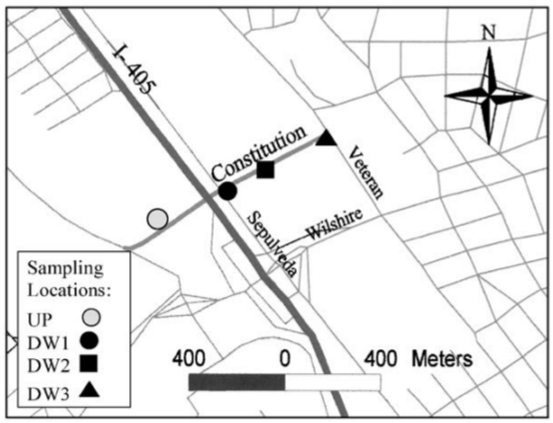

Figure 2.2 Freeway Site and Sampling Locations in Los Angeles (Sabin et al., 2006).

It was determined for the Los Angeles site that the deposition flux of copper was high close to the source and rapidly reduced to urban background levels well within 150 m; this is shown in Figure 2.3 and Table 2.1. The vast majority of the copper that was deposited adjacent to the roadway was deposited within 10 m from the highway (Sabin et al., 2006). Note that the location that is 150 m upwind of the freeway reflects probable background levels of air deposition in this area, and it is the difference between these background values and the measurements at 10, 150, and 450 m downwind of the freeway that can be attributed to freeway sources of these metals.

Table 2.1 Mean Dry Deposition Flux ± Standard Deviation (μg/m²/day) of Metals Measured at Varying Distances from the I-405 Freeway (Sabin et al., 2006)

Location	Chromium	Copper	Nickel	Lead	Zinc
10 m Downwind (DW1)	4.3±0.3	48±8	3.1±0.6	24±3	144±33
150 m Downwind (DW2)	2.4±1.9	18±7	1.0±1.3	11±4	45±23
450 m Downwind (DW3)	2.5±1.1	14±3	1.2±1.1	7.3±1.8	38±1
150 m Upwind (UP)	2.2±0.5	11±5	1.5±0.9	7.9±1.3	37±10

$N = 3$ for all metals.

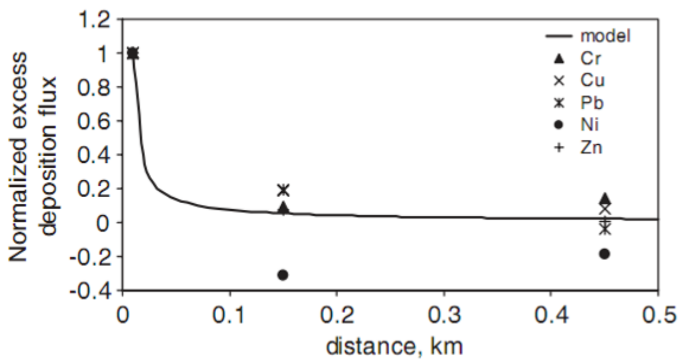

Figure 2.3 Comparison of Computed and Measured Normalized Excess Deposition Flux in Los Angeles (Line is steady-state prediction using a wind speed of 2 m/s and a deposition velocity of 1 cm/s.) (Sabin et al., 2006)

In another study, three sites (Figure 2.4) at two cities in Texas (Austin and College Station), were monitored to see how the antecedent dry period affects copper concentrations in first-flush runoff. Passive first-flush samplers were installed. The traffic count for the one Austin site was 43,000 and 35,000-vehicles/day for the other Austin sites. Average daily traffic was greater than 50,000 vehicles for all College Station sites. College Station experiences 8-9% heavy vehicle traffic such as trucks while the Austin sites were located in a residential area. None of the sections had curbs (Li and Barrett, 2008).

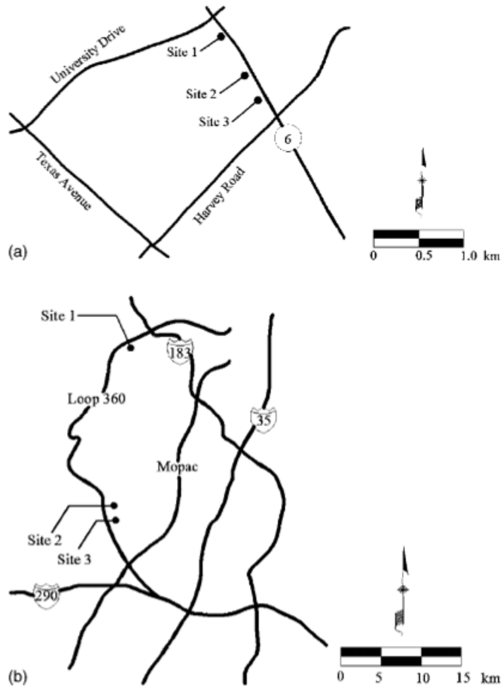

Figure 2.4 Map of Sites - (a) College Station, (b) Austin (Li et al., 2008)

At the Austin sites, results were as expected (Figure 2.5). As the antecedent dry period (ADP) increased, so did first-flush copper concentrations. However, this was not true of the College Station sites (Figure 2.6). As the ADP increased, the runoff copper concentrations actually decreased. From this, the authors suspect that pollutant buildup occurs on high traffic roads at the end of the event when runoff is no longer occurring, but the wet roads are still washing pollutants off of vehicles, as shown in Figure 2.7. If the highways had curbs, which they do not, the pollutants would also accumulate along the curb resulting in high pollution concentration from the first flush. However, on highways without curbs, the pollutants are moved gradually to the grassy areas on either side of the highway (Li and Barrett, 2008).

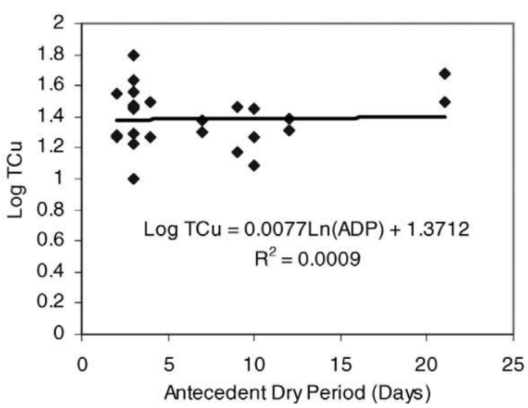

Figure 2.5 Relationship Between ADP and Copper Concentration at Austin Site (Li and Barrett, 2008)

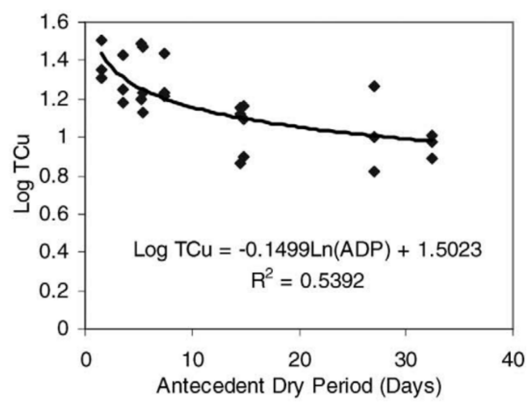

Figure 2.6 Relationship Between ADP and Copper Concentration at College Station Site (Li and Barrett, 2008)

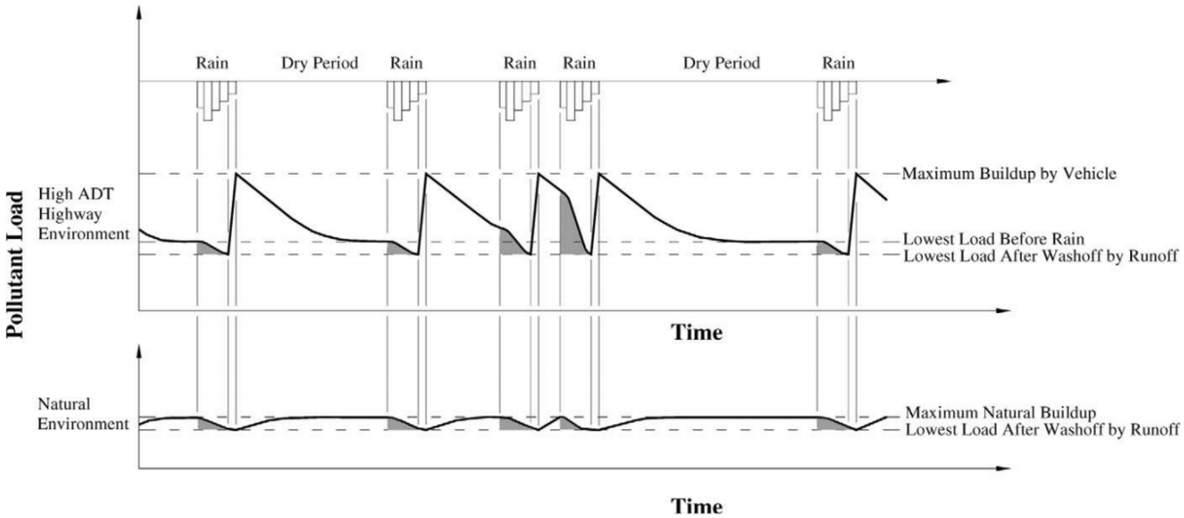

Figure 2.7 Conceptual Models of Pollutant Buildup and Removal Processes (shaded areas represent runoff transported pollutant quantity) (Li and Barrett, 2008).

The graph above reflects the author's theory and has not been fully tested and confirmed. Due to the fact that copper does not decay like other tested elements in this study, it is unlikely that this concept is representative of the Bay Area. Also, these studies were conducted in an area that receives 86% more rain than the Bay Area, and significant rainfall in every month of the year, where the Bay area has almost no rainfall from May to August. Therefore, the time between events in the Austin area is likely shorter. Longer dry periods between events allows more time for copper deposition from brakes and other sources.

Burton-in-Kendal, Cumbia, in England was the site of a study where deposition flux was measured 60 meters from the centerline of a major rural highway. Sampling transects perpendicular to the road were set up on the east and west sides of the M6 motorway located 3 km north of the city. Monitoring duration was 1 year, during which the traffic count was 32,000 gasoline cars/day and 5,600 diesel vehicles/day (Hewitt and Rashed, 1991). The climate of Burton-in-Kendal is unlike the Bay Area; the area receives significantly more precipitation, and the temperatures are considerably cooler.

Results from the study conducted in Burton-in-Kendall, Cumbia (Figure 2.8) also demonstrate that copper deposition occurs only in a very narrow band along the road. This is because pollutants associated with very large particles have high deposition velocities and deposit close to the source and atmospheric dispersion will dilute the concentrations with increasing distance. Only a very narrow band of 20-40 m on either side of the highway will experience any noticeable deposition and the majority of it will be deposited within 10 m from the shoulder as Figure 2.8 demonstrates (Hewitt and Rashed, 1991).

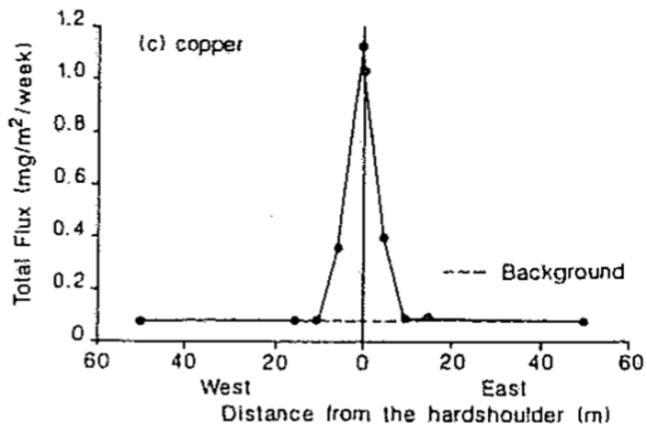

Figure 2.8 Average Deposition Flux of Copper Adjacent to the M6 Roadway (Hewitt and Rashed, 1991).

In another study, two 50 m transects (Park and School) were set up in Honolulu, Hawaii (see Figure 2.9). These transects were selected because of their differences in traffic volume and sidewalk architecture. Soil samples were collected at 10, 20, 30, 40, and 50 meters from the road on both transects. Both locations carry low-speed traffic below 40 km/hr. Average traffic for the area is 45,200 vehicles/day (Sutherland and Tolosa, 2001). Honolulu is very similar to the Bay Area as it receives little rainfall in the summer.

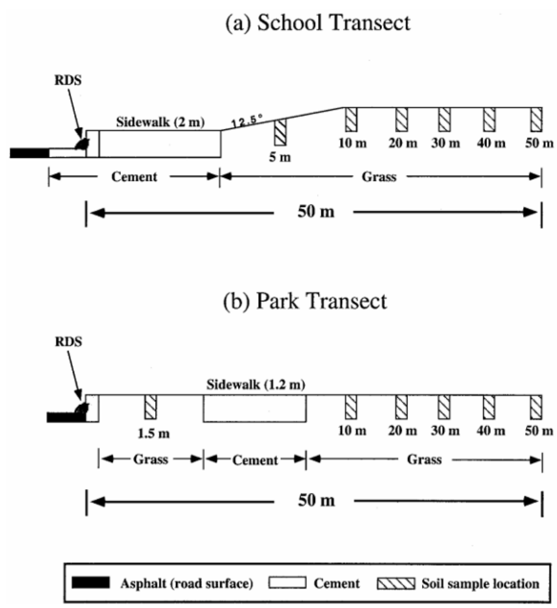

Figure 2.9 Schematic of Transects in Hawaii (RDS is Road Deposited Sediment) (Sutherland and Tolosa, 2001)

In Honolulu, "all available data suggest a rapid fallout of copper with distance from road surfaces, with Park samples at distances ≥ 10 m little different from background concentrations" (Sutherland and Tolosa, 2001). However, at the School transect, this was not the case, the nearest soil samples, located at 5 m from the road showed no significant higher concentration in copper than locations 50 m from the road (Figure 2.9). This is most likely due to the road-curb-sidewalk-soil architecture of the sampling cross section. The road-curb-soil-sidewalk architecture allowed for samples to be taken much closer to the road (Sutherland and Tolosa, 2001).

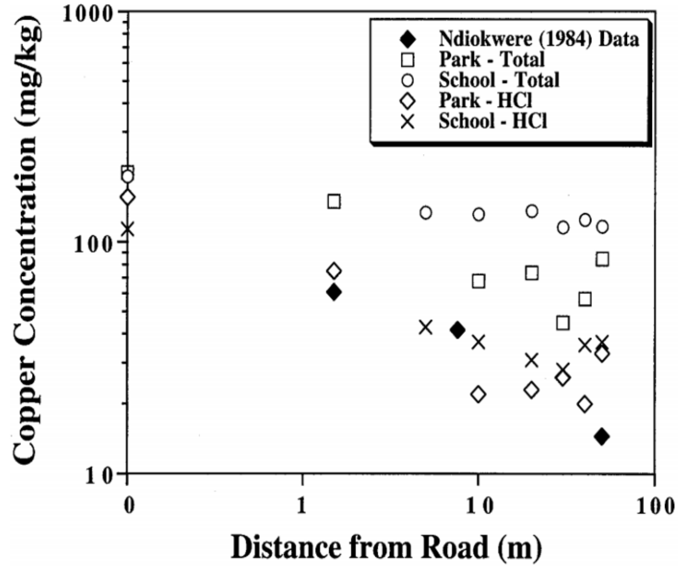

Figure 2.10 Spatial Variation in Copper with Distance from Road for Upper Soil from School and Park Samples for Total Digestion and 0.5 M HCl Extraction (Sutherland and Tolosa, 2001)

In another study, soil core samples were collected outside of Nantes (Erdre), and Houdan (Houdan), France. The Erdre site has approximately 24,000 vehicles/day, of which 7% is heavy vehicle traffic, and the speed is 130km/h. In 1996 it was repaved with porous asphalt. The Houdan site is paved with conventional asphalt and experiences 10% heavy vehicle traffic and 21,000 vehicles/day. Both sites have a hard shoulder and prevailing winds run longitudinally along the roads (Legret and Pagotto, 2008). France receives more rainfall throughout the year than the Bay Area.

The results of a study conducted in France were similar to the results of the other studies as it was found that pollution transported from the road remains close to the road as “at the Houdan site…no input in excess of the background level was found at a distance of 6 m” (Legret and Pagotto, 2008) (see Table 2.2 and Figure 2.11). This study confirmed the study done by Li and Barrett (2008) as well indicating that wet deposition is the major process by which heavy metals are deposited on the road surface, as the rainy months also experienced the greatest copper deposition (see Figures 2.12 and 2.13) (Legret and Pagotto, 2008).

Table 2.2 Heavy Metal Content in Soil at the Houdan Site (Legrett and Pegatto, 2008)

Distance	Cd	Cr	Cu	Pb	Zn
			mg kg^{-1}		
0.50 m					
0-2 cm	1.58	43	173	364	338
2-10 cm	1.85	39	99	683	338
10-30 cm	1.39	33	54	434	198
5 m					
0-2 cm	0.24	52	14	61	57
2-10 cm	0.21	54	11	54	48
10-30 cm	0.17	56	14	23	45
25 m					
0-2 cm	0.15	53	9	44	41
2-10 cm	0.11	52	8	37	38
10-30 cm	0.11	47	9	20	35

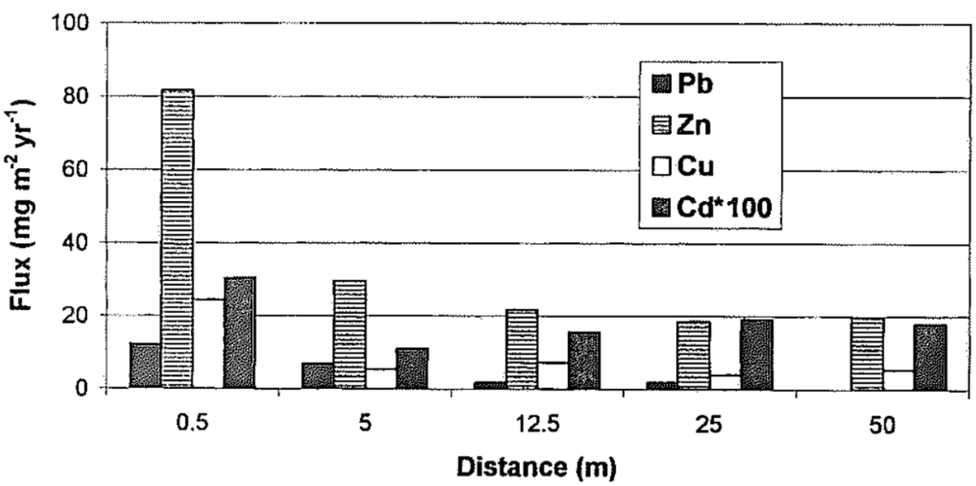

Figure 2.11 Heavy Metal Deposition at the Erdre Site (Legret and Pegatto, 2008)

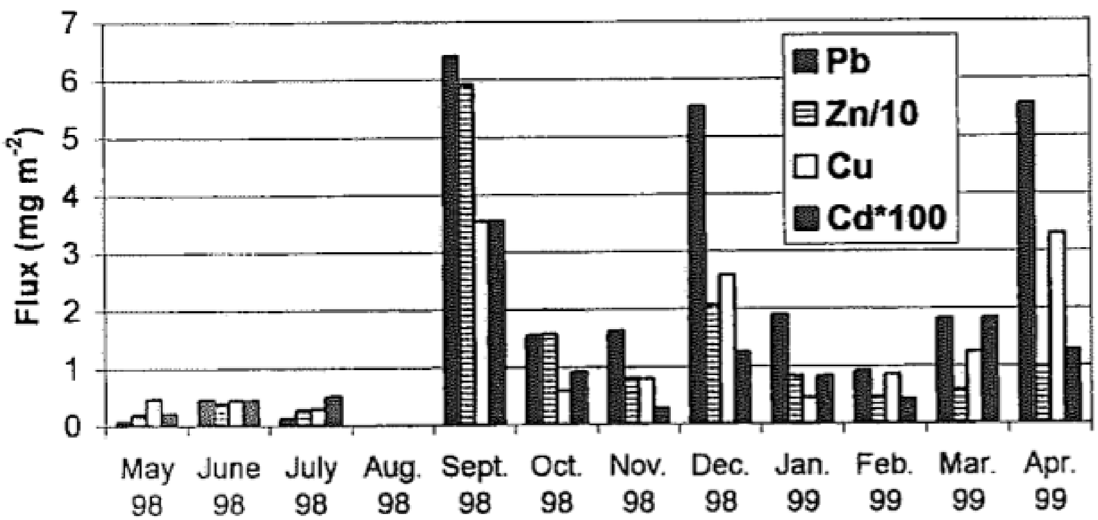

Figure 2.12 Monthly Total Deposition at the Erdre Site at 0.5m from the Road (Legret and Pagatto, 2008)

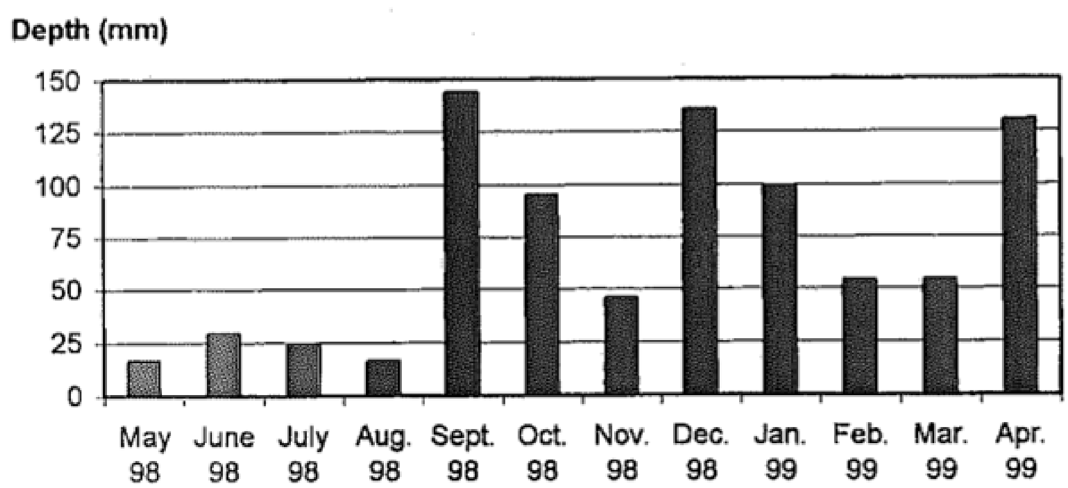

Figure 2.13 Monthly Rainfall at the Erdre Site (Legret and Pegatto, 2008).

The last study that was reviewed consisted of two transect sites that were set up in Norsholm and Svaneberg in Sweden. In Norsholm the traffic count is 15,600 vehicles/day, 13% of which are heavy vehicles; and in Svaneberg the traffic count is 7400 vehicles/day, 16% of which are heavy vehicles. The roads are flat and have posted speed limits between 90 and 110 km/hr. Total deposition samples were collected at the downwind side of the road in Svaneberg at 1, 5, 30, and 200 meters from the road. In Norsholm, samples were taken at the downwind side of the road at 2, 6, 30, and 400 meters from the road (Backstom et al., 2003). Although the average annual precipitation is the same for this area as it is for the Bay Area, unlike the Bay Area, Sweden gets the majority of its precipitation in the summer months. It is about 5 degrees cooler in this region of Sweden in the summer and about 25 degrees cooler in the winter than the Bay Area.

At Svanberg, background concentrations are reached within 5 meters of the road, and a little farther out at Norsholm, as is shown in Figure 2.14 (Backstrom et al., 2003).

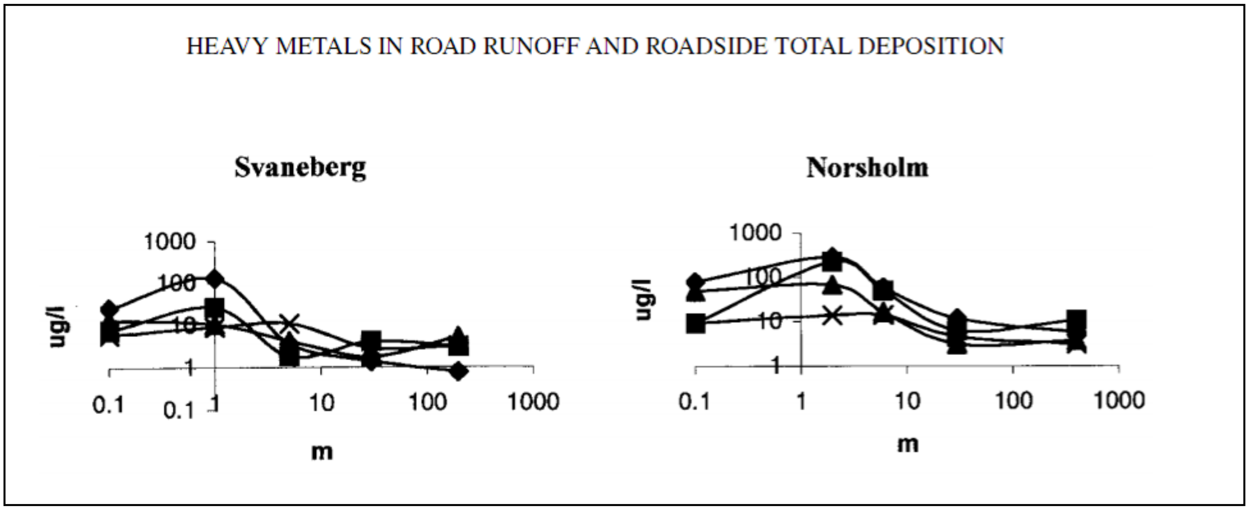

Figure 2.14 Metal Concentrations as a Function of Distance from Roadway (Note: the solid squares represent concentrations in the summer, which is closer in climate to the Bay area than the winter months (diamond shape) as the precipitation would be rain and not snow. Distance at 0.1 m represents runoff) (Backstrom et al., 2003).

2.1.3 Conclusion

Copper disperses from the roadway and reaches background levels (levels that are found in areas that are not directly affected by roadway copper) within approximately 10 meters, sometimes within as little as 5-6 m. Deposition fluxes and copper in soil results from these studies are summarized in Figures 2.15 and 2.16, respectively.

For all studies discussed, the furthest that copper concentrations above background concentrations are deposited is 12 m, in spite of the very different weather, vehicle speeds and daily traffic of the areas discussed. While factors such as wind, vehicle travel, rain, and vehicle type do play a role, it is not a dominant role in determining the distance from the road that copper will disperse. Figure 2.17 provides a comparison of the typical rainfall patterns at the locations of the cited studies.

Based on this information, a buffer width of 10 m was chosen for this portion of the Phase 2 modeling.

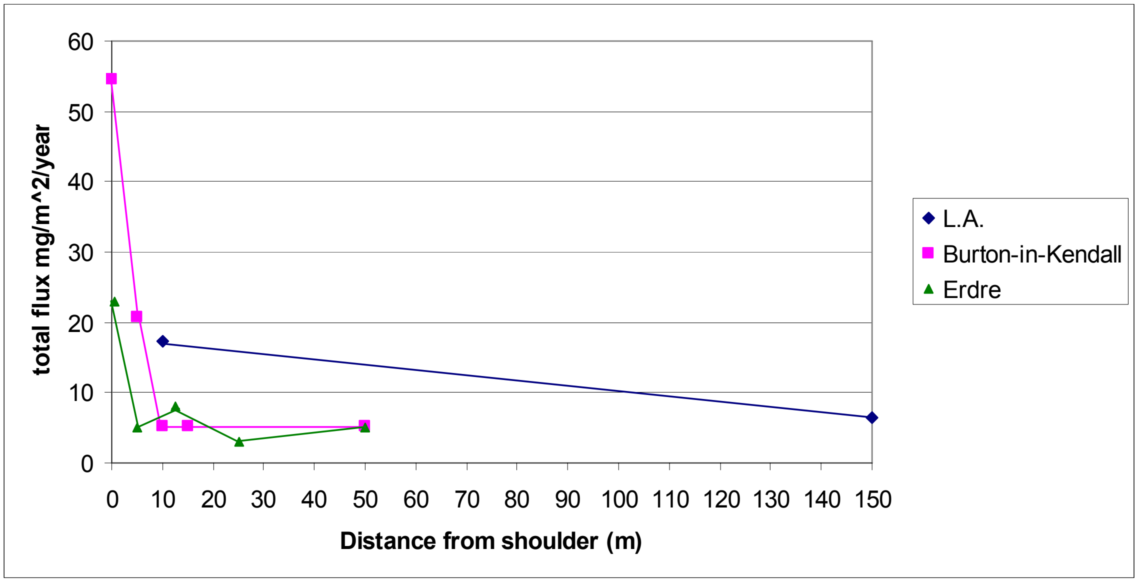

Figure 2.15 Superposition of Results from Studies Discussed.
(Note: "Burton-in–Kendall" and "Erdre" values were taken from a graph and may not be exact. Also, the Los Angeles plot represents only dry deposition while the others represent wet and dry deposition.)

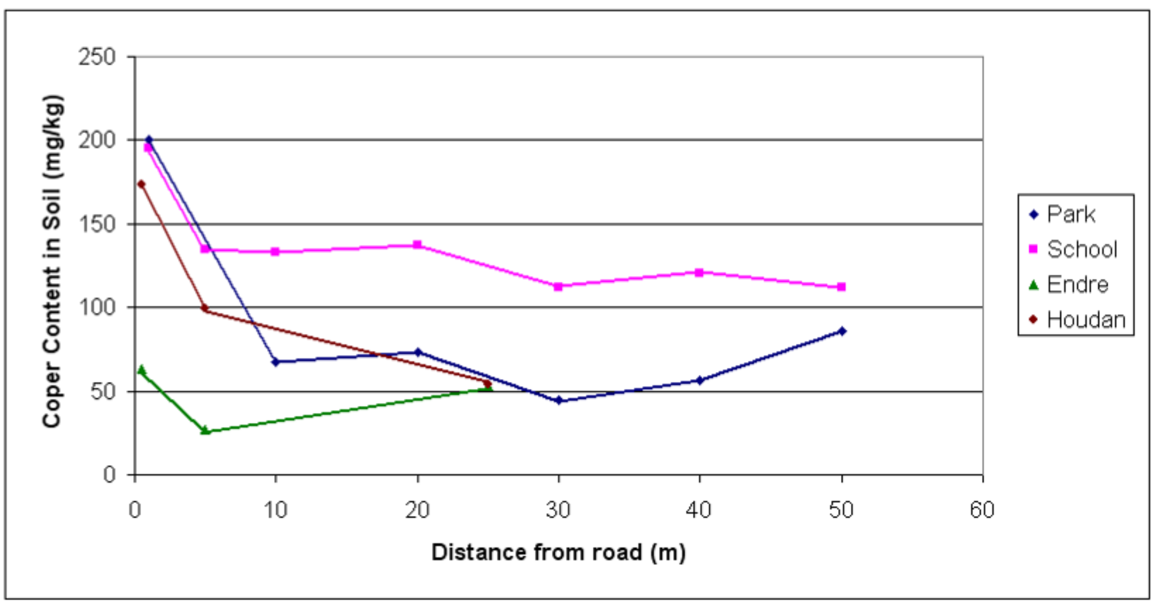

Figure 2.16 Superposition of Soil Copper Content from Studies Discussed
(Note that "Park" and "School" were taken from a graph and may not be exact.)

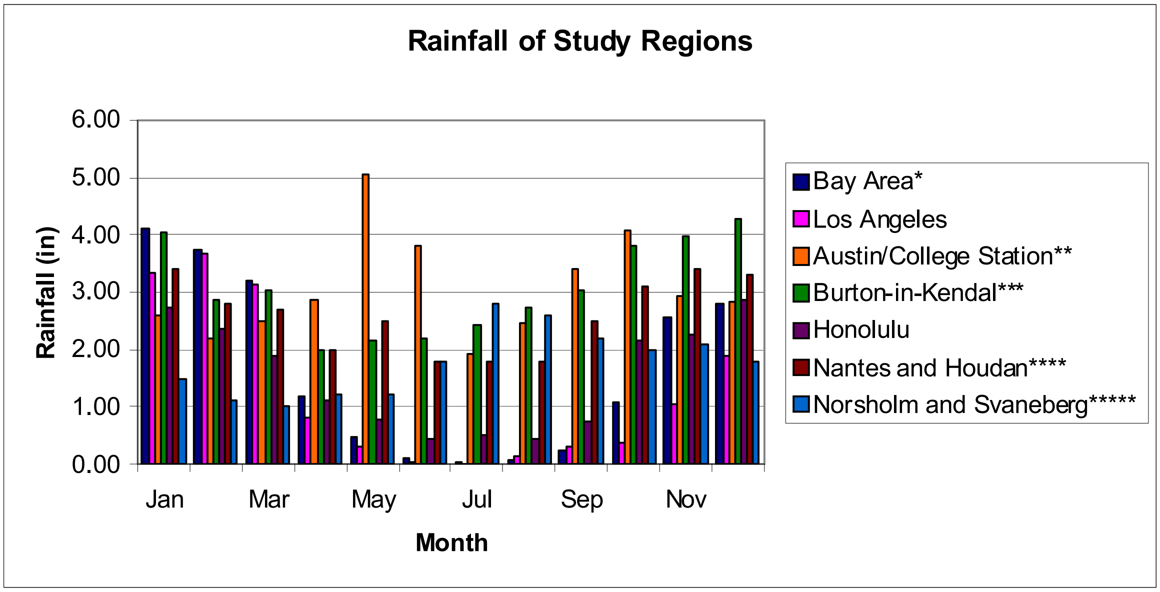

Figure 2.17 Average Monthly Rainfall of Studied Areas
(* Bay Area is an average of the data from San Francisco, South San Francisco, San Mateo, Mountain View, Milpitas, Fremont, Hayward, and Oakland.
**** Average of Austin and College Station**
***** Burton-in-Kendal not available, Burton data**
****** Nantes not available, Houdan data**
******* Norsholm and Svaneberg not available, Stockholm data)**

2.2 EFFECTS OF BUILDUP/WASHOFF MODELING TECHNIQUES AND PARAMETERS ON COPPER LOADING

The modeling techniques evaluated and studied in this effort include the following:

1. Impact of copper 'loss' due to Phase 1 buildup/washoff modeling techniques, and subsequent deposition on both pervious and impervious buffers,
2. Sensitivity analyses of the impacts of the accumulation limit and the bed sediment exchange rate,
3. Impacts of engineered concrete channels, as opposed to natural channels, in the Upper Colma sub-watershed

Each of these issues originated from either prior knowledge of the modeling techniques and their potential impacts, and/or from discussions with the Brake Pad Partnership Steering Committee; each are addressed in the sections below

2.2.1 ANALYSIS OF APPLYING COPPER LOST FROM ROADWAYS TO ROADSIDE BUFFERS

The primary methodology for investigating the Phase 1 modeling's buildup-washoff technique consisted of computing the amount of copper "loss" in each time increment from the roadways/impervious area, and transferring this loss directly to a new land area (called a buffer) adjacent to the impervious area. This land area was estimated as equal to a buffer width along both sides of the roadway, with the buffer width equal to the roadway width. This buffer width corresponds to the findings of the literature review about copper deposition adjacent to roadways. The total area was computed as two times the area of all road surface area in each sub-watershed, based on road surface values for each sub-watershed developed by URS (Dufour and Cooke, 2006). This methodology is illustrated in Figure 2.18. The equivalent area was removed from the developed pervious area. The buffer was assumed to be modeled the same as the other developed pervious areas in each sub-watershed, with the additional inputs of “lost” copper from the impervious areas. In a second set of model runs, the buffer areas were assumed to be impervious instead of pervious. The impervious buffer was modeled the same as the other impervious areas in each sub-watershed. This option is assumed to represent a worst-case for the buffer modeling technique, since a larger fraction of copper that accumulates on impervious areas becomes entrained in stormwater compared to copper that has accumulated on pervious areas.

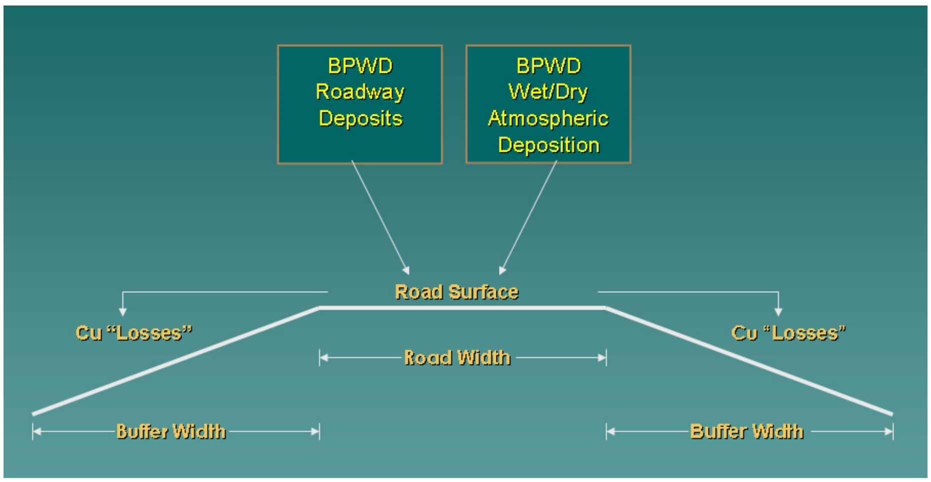

Figure 2.18 Conceptual Approach to Roadway Buffers that Receive Copper Losses Due to Buildup-Washoff Approach

Investigations into the effects of adding the lost copper to the buffer areas were made using the Special Actions feature in HSPF. This feature allows model state variables and fluxes to be queried and reset at any time interval. It also allows computations of intermediate values based on the state variables and fluxes. Each time step of the run, the amount of lost copper on the roadway/impervious area was computed, and was then added to the copper storage on the adjacent buffer area. Since HSPF land areas are modeled on a unit area basis, the mass of lost copper was scaled by the ratio of the area of the buffer to the area of the roadways, e.g., if 5 lbs are lost from a 1-acre road surface, and it is deposited onto a 2-acre buffer, the loading rate onto the buffer will be 2.5 lbs/acre, to maintain a mass balance.

Table 2.3 shows the effects of the roadway buffers on copper loading to the Bay on an average annual basis for the five example sub-watersheds. The results show an impact of approximately 20% to 30% for an impervious buffer, but a relatively minor impact if the buffer is pervious. In actuality, roadway buffers are a mix of pervious and impervious, and these values provide a potential range of the bias in the copper loads in runoff in the Phase 1 report.

Table 2.3 Effects of Roadway Buffers on Copper Loads*

Sub-Watershed (% impervious)	Copper Load to the Bay, Phase I Modeling (Mid Brakes Case), kg/yr	100% Pervious Buffer, Phase II Modeling		100% Impervious Buffer, Phase II Modeling	
		Copper Load to Bay (kg/yr)	% Change from Phase I Results	Copper Load to Bay (kg/yr)	% Change from Phase I Results
East Bay North (37%)	1,781	1,845	3.6%	2,045	15%
Peninsula Central (16%)	2,682	2,723	1.5%	3,452	29%
Petaluma (0.2%)	4,742	4,772	0.6%	5,689	20%
Santa Clara Valley Central (6%)	2,645	2,704	2.2%	3,478	31%
Upper Colma (27%)	521	539	3.3%	648	24%

*Includes the loads from brake pad sources, anthropogenic non-brake sources, and sediment.

In the Phase 1 report, where the lost copper from the buildup and washoff function was unaccounted for, releases of copper from brake wear debris (as opposed to the contribution from non-brake anthropogenic sources or background sediment) were estimated to contribute 36% of all the copper found in runoff in the East Bay North sub-watershed (median estimate case). When this lost copper is accounted for by applying it to adjacent roadway buffer, the contribution from brakes ranges from 38% to 44%, depending on whether the buffer is pervious or impervious. For the Peninsula Central sub-watershed, the contribution from brakes becomes 50% to 60% instead of 49%. In the Petaluma sub-watershed, the contribution from brakes becomes 8% to 22% instead of 7%. In the Santa Clara Valley Central sub-watershed, the contribution becomes 30% to 45% instead of 28%. In the Upper Colma sub-watershed, the contribution becomes 52% to 60% instead of 50%. Table 2.4 summarizes these results.

Table 2.4 Effect on the Relative Contribution of Copper from Brake Pads to Copper Loads to the San Francisco Bay of Applying Copper "Lost" in the Buildup and Washoff Functions to Roadway-Adjacent Buffer

Sub-Watershed (% impervious)	Relative Contribution of Copper from Brake Pads (% of total load of copper)		
	Phase I Modeling (Median Estimate Case)	100% Pervious Buffer, Phase II Modeling	100% Impervious Buffer, Phase II Modeling
East Bay North (37%)	36%	38%	44%
Peninsula Central (16%)	49%	50%	60%
Petaluma (0.2%)	7%	8%	22%
Santa Clara Valley Central (6%)	28%	30%	45%
Upper Colma (27%)	50%	52%	60%

2.2.2 ANALYSIS OF ACCUMULATION LIMIT

In addition to the accumulation rate, the other key parameter in the buildup/washoff modeling technique is the accumulation limit, which is designated SQOLIM in HSPF. This represents the maximum amount of copper that can exist on the land as a result of the accumulation parameter ACQOP. Typically, SQOLIM is a calibration parameter, and is set to a specific number of days of accumulation for both pervious and impervious land categories; the inverse of SQOLIM, i.e., 1/SQOLIM, is the effective first-order removal (or loss) rate in units of fraction lost per day (1/day). In Phase 1, the range of values for SQOLIM varied between 22 days and 45 days, with the lower values for the developed land uses (both pervious and impervious) and the larger values for the other categories.

A sensitivity analysis of SQOLIM was performed for the example sub-watersheds to determine the effect of varying this parameter for all land uses. The results of this test are shown in Table 2.5, for a set of multipliers applied to SQOLIM, varying in a range between 0.5 and 2.0, i.e., halving and doubling the Phase 1 value. Increasing the SQOLIM reduces the loss rate, and thus leads to more copper available to washoff, and vice versa. Unlike the examination of lost copper, there is no known bias in the Phase 1 results; although the accumulation limits are consistent with past studies, there was insufficient calibration data to confirm these values in Phase 1. Instead, this investigation was done to explore the sensitivity of the model results to uncertainties in the accumulation limits.

The results in Table 2.5 demonstrate this relationship and show a significant sensitivity, with copper loads changing in the range of 20% to 40%, for the extreme changes (i.e., 0.5 and 2.0) for the more urbanized sub-watersheds, but much less (i.e., 6% - 7%) for the rural Petaluma sub-watershed. Thus the SQOLIM parameter and its corresponding effective loss rate have a significant impact on copper loads. The uncertainty in the accumulation limits could be reduced by extending the calibration efforts.

Table 2.5 Effect of Varying Accumulation Limit SQOLIM on Copper Loads

	SQOLIM								
Multiplier of SQOLIM	x 0.5		x 0.75		x 1.0	x 1.5		x 2.0	
	Load to Bay (kg/yr)	% Chg from Mid Brakes	Load to Bay (kg/yr)	% Chg from Mid Brakes	Mid Brakes Load to Bay (kg/yr)	Load to Bay (kg/yr)	% Chg from Mid Brakes	Load to Bay (kg/yr)	% Chg from Mid Brakes
East Bay North	1,366	-23.3%	1,592	-10.6%	1,781	2,097	17.7%	2,364	32.7%
Peninsula Central	2,104	-21.5%	2,421	-9.7%	2,682	3,114	16.1%	3,475	29.6%
Petaluma	4,478	-5.6%	4,624	-2.5%	4,742	4,934	4.1%	5,090	7.3%
Santa Clara Valley Central	2,192	-17.2%	2,439	-7.8%	2,645	2,759	4.3%	3,289	24.3%
Upper Colma	309	-40.7%	458	-12.2%	521	627	20.3%	716	37.4%

2.2.3 ANALYSIS OF STREAM BED STORAGE AND COPPER EXCHANGE RATES

The Phase 1 modeling identified the stream sediments as a reservoir of copper. The two primary determinants of the amount of copper stored in the streambeds are the mass of sediment and the sorption parameters, in particular the rate of copper adsorption/desorption or exchange. A sensitivity analysis of the copper exchange rates was performed for the example sub-watersheds to determine the effect of varying this parameter, which is relatively uncertain. The rates in the Phase 1 model were set at a value of 0.02 day^{-1}, which represents a half-life of approximately 35 days. The rates were varied between 0.001 day^{-1} and 2.0 day^{-1}. The results of this test are shown in Table 2.6.

Table 2.6 Effect of Varying Copper-Sediment Exchange Rate on Copper Loads

	Rate(/day) / Half Life (days)										
	0.001/693		0.01/69.3		0.02/34.7	0.1/9.63		0.2/3.47		2.0/.347	
	Load to Bay (kg/yr)	% Chg from Mid Brakes	Load to Bay (kg/yr)	% Chg from Mid Brakes	Mid Brakes Load to Bay (kg/yr)	Load to Bay (kg/yr)	% Chg from Mid Brakes	Load to Bay (kg/yr)	% Chg from Mid Brakes	Load to Bay (kg/yr)	% Chg from Mid Brakes
East Bay North	1,818	2.0%	1,789	0.4%	1,781	1,771	-0.6%	1,769	-0.7%	1,769	-0.7%
Peninsula Central	2,712	1.1%	2,689	0.3%	2,682	2,667	-0.5%	2,664	-0.7%	2,660	-0.8%
Petaluma	4,719	-0.5%	4,737	-0.1%	4,742	4,753	0.2%	4,756	0.3%	4,762	0.4%
Santa Clara Valley Central	2,719	2.8%	2,649	0.1%	2,645	2,668	0.8%	2,684	1.4%	2,723	2.9%
Upper Colma	536	2.9%	525	0.6%	521	516	-1.0%	515	-1.2%	514	-1.5%

Generally, the effects of exchange rates on copper loading to the Bay were shown to be small. As the exchange rates increase, copper loads generally would be expected to decrease because less copper would be sequestered in the sediments; it would desorb more quickly and flow to the Bay during periods of low dissolved copper concentrations. Conversely, lower rates would be expected to result in more copper in the sediments. (Note: the effect of the exchange rates is also a function of the flow-through time in the reaches, so the length of the channel reaches will have an impact.) This behavior was observed in three of the sub-watersheds, i.e., Upper Colma, East Bay North, and Peninsula Central. In sub-watersheds where the amount of copper sequestered in the sediments was relatively low, such as Petaluma due to low brake contributions, the expected behavior was reversed.

In the Petaluma sub-watershed, there is much more sediment (and sediment-associated copper) that erodes from the land surface and discharges to the Bay. As a result, there is a net loss of copper from the bed sediments throughout the simulation period. This net loss is likely caused by copper desorbing from the bed sediment and subsequently adsorbing to the higher sediment concentrations in the water column during storms. When the bed exchange rates are higher, the loss from the bed increases. The copper that is lost from the bed enters the water column and is discharged to the Bay.

The Santa Clara Valley Central sub-watershed exhibits different behavior than the other sub-watersheds. Copper loads to the Bay increase as the exchange rates both increase and decrease from the base/Phase 1 scenario. Furthermore, the percentage change in copper loads is higher than the other sub-watersheds, but still relatively minor. It is coincidental that the Phase 1 exchange rates provide the lowest possible copper loading to the Bay – everything else being equal. Since there is net copper adsorption to bed sediments in this sub-watershed, presumably **lower** exchange rates allow less of the runoff copper to adsorb to the bed, and therefore more copper flows to the Bay. Since the sediment loads in this sub-watershed are relatively high (but not as high as Petaluma), it is possible that the effect that is observed in Petaluma at **higher** exchange rates dominates, and therefore also causes higher copper discharge to the Bay. The analysis time/effort required to definitively determine the cause of this behavior was deemed to be relatively high, and therefore, was not undertaken, since the overall effects on copper loads were so small.

2.2.4 ANALYSIS OF ENGINEERED CONCRETE CHANNEL IN THE UPPER COLMA SUB-WATERSHED

A model run was made for the Upper Colma sub-watershed to determine the effects of converting the creek to an engineered concrete channel that would have little or no sediment bed. This was done by changing the initial sediment bed to zero, and setting the sediment transport parameters so that all sediment that enters the reach is transported through to the Bay, i.e., no deposition. The resulting loads to the Bay over the 25-year simulation span were compared with the Phase 1 median estimate loads in Table 2.7. During the first few years, the copper load is much higher, since copper is no longer being adsorbed to bed sediments. After several years, when the bed sediment in the Phase 1 run had been essentially saturated (additional copper loading from the sub-watershed remains in solution), the transported copper load returns approximately to the base values.

The results of this indicate that copper levels in the stream bed sediments can become effectively saturated after many years of high copper loading, and subsequently start to behave like channelized stream courses where little adsorption to stream bed sediment is possible. For natural streams, the saturation of the bed inhibits copper exchange, whereas for channelized streams the lack of bed sediment is the limiting factor in the exchange process. Thus, the modeling showed relatively small long-term differences in these two conditions but for different reasons.

Table 2.7 Effect of Engineered Reach on Copper Loads Delivered from Upper Colma

	MidBrakes	Engineered-RCH	
	Cu Load to Bay (kg/yr)	Cu Load to Bay (kg/yr)	% Chg
Mean	521	541	3.7%
1981	181	255	41%
1982	607	720	19%
1983	629	712	13%
1984	432	487	13%
1985	376	425	13%
1986	678	711	4.9%
1987	285	302	6.1%
1988	421	449	6.6%
1989	404	444	9.7%
1990	311	332	6.7%
1991	290	302	4.0%
1992	490	496	1.1%
1993	590	586	-0.6%
1994	337	341	1.2%
1995	829	818	-1.3%
1996	611	602	-1.5%
1997	764	761	-0.4%
1998	1,067	1,043	-2.2%
1999	512	522	2.1%
2000	498	506	1.7%
2001	388	393	1.4%
2002	568	559	-1.6%
2003	507	504	-0.6%
2004	595	583	-2.0%
2005	665	661	-0.5%

SECTION 3.0

EFFECTS OF BRAKE-RELATED SOURCE REDUCTIONS ON COPPER LOADING

3.1 METHODOLOGY FOR ASSESSING THE TIME FOR SOURCE REDUCTIONS TO TAKE EFFECT

The objectives of this part of the Phase II study were to assess the recovery time required for the extra stored copper to wash out of the system after implementation of source controls on brake pad copper, and also explore the sensitivity of this recovery time to variation in long-term meteorological conditions. For each example sub-watershed, three meteorological scenarios were investigated: a historical scenario, a dry scenario, and a wet scenario. This section describes the modeling approach for simulating the effect of ceasing brake pad copper contributions on loads discharged to San Francisco Bay and defines a metric for depicting changes in loads.

A series of model runs was devised to assess the “lag” time after brake-related sources have been turned off until copper loads approach the baseline loads. Figure 3.1 shows the brake sources that are curtailed in these scenarios. For each sub-watershed and each precipitation scenario, three simulation runs were needed to evaluate the time needed to approach baseline conditions, as follows:

> **Brake Sources- Unchanged** – This simulation provides loads under conditions of brake sources; i.e., essentially the same, or unchanged, as implemented in the Phase 1 simulation. In this run, the initial copper storages were set to the values at the end of the Phase 1 median estimate model run. This reduces the start-up effects, primarily of copper adsorbing to bed sediments. As a result, these runs exhibit slightly higher loads for several years compared to the Phase 1 runs.
>
> **Baseline** - This simulation provides loads under conditions of **zero brake sources,** but all other non-brake sources remain as in the Phase 1 simulations. The initial copper storages in this run were set to the values at the end of the Phase 1 - no-brake model run. This should represent conditions after a long period of no brake sources, and is essentially the same as the Phase 1 no-brake run except for the reduced start-up effects that result from the revised initial conditions.
>
> **Brake Sources- Off** – This simulation provides copper loads for 25 years following the cessation of the brake sources at time = 0. The initial copper storages in this run are the same as those in the Brake Sources-Unchanged run, i.e., this is assumed to represent conditions after a long period of existing brake-related sources.

As mentioned above, in all three of these simulations, the initial copper storages in the soil and the stream sediment were set to remove the effects of the “start-up”, in particular on the copper adsorbing to stream bed sediments. Since this analysis is sensitive to the effects of the start-up, it was decided to eliminate them as much as feasible.

At any time during the simulation, the difference between the annual Brake Sources-Unchanged and Baseline loads represents the brake-derived copper under the Brake Sources-Unchanged conditions, i.e., the Phase 1 brake contribution in each year. Likewise, the

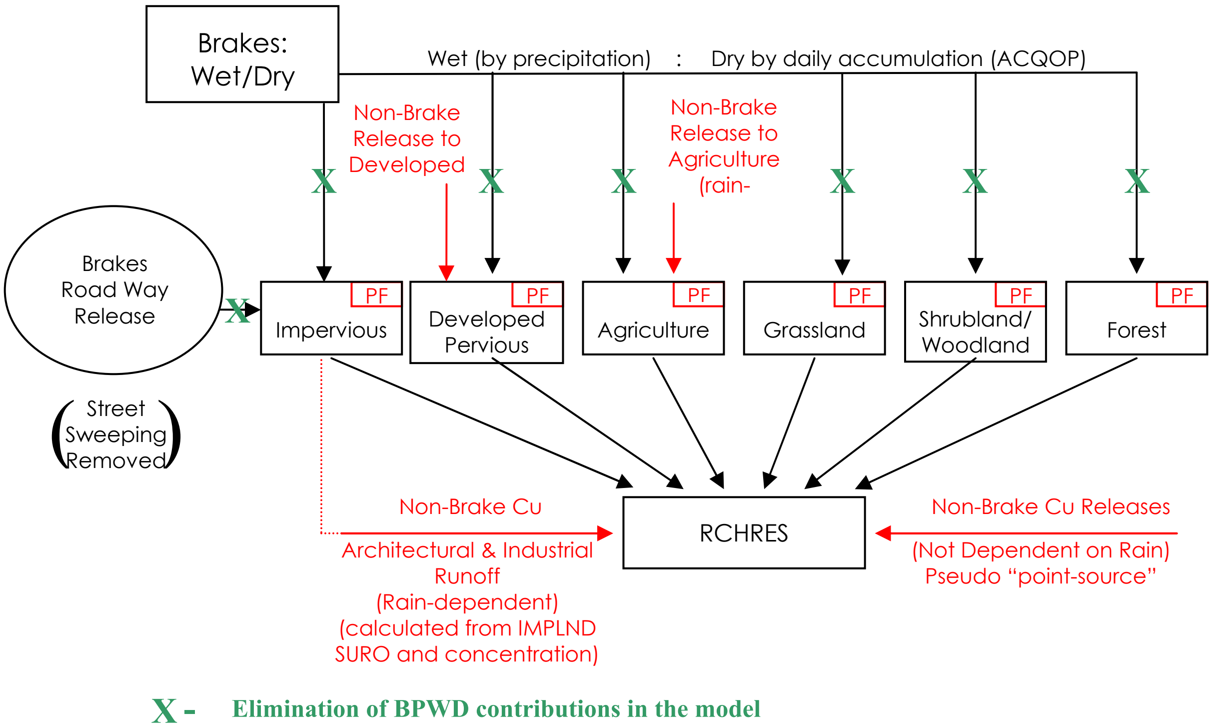

Figure 3.1 Copper Flux Diagram in the Model with Brake Sources Stopped

difference between the Brake Sources-Off and Baseline loads represents brake-derived copper under the Brake Sources-Off conditions, i.e., after brake sources have been stopped. The ratio of these two quantities (see below) over time provides a measure of the approach to Baseline copper loads, calculated as follows.

$$\frac{\textbf{(Brake Sources-Off – Baseline)}}{\textbf{(Brake Sources-Unchanged – Baseline)}} = \textbf{fraction of brake-derived copper that occurred during that year}$$

As this fraction approaches zero, annual copper loads approach Baseline conditions. Similarly, one minus this fraction is a measure of the **reduction** in brake-derived copper loads that has occurred during that year. A plot of these fractions or percentages with time provides a representation of the reduction in brake derived loads with time, and the subsequent approach to Baseline copper loads.

3.2 METEROLOGIC CONDITIONS – HISTORICAL, DRY, AND WET SCENARIOS

In addition to assessing the time it takes for copper loads to approach the baseline under historical meteorological conditions, the same analyses were performed under both wet and dry meteorological conditions to assess the impacts of climate variability. Figures 3.2–3.6 show the historical precipitation from about 1950 to 2006, for five stations around the Bay: San Francisco, San Jose, Berkeley, Livermore, and Napa. These five locations represent the range of precipitation within the Bay Area, and are a subset of the 20 stations used in the Phase 1 SF Bay Watershed modeling work.

The plots also show the mean annual precipitation for each station, along with the 3-year and 5-year moving average; these last two statistics provide a better display of the wet and dry cycles of the past 50+ years in the Bay Area. Note the definitive dry cycles in the 1975-81 and 1984-94 time periods, and the wet cycles during the 1982-86 and 1995-2005 periods. Also, it's interesting to note that the cycles are tending to show greater fluctuations (amplitudes) since about 1980. This could be a possible consequence of climate change, noted in the scientific literature, although the overall time period is relatively short with only a few cycles obvious during the entire time period.

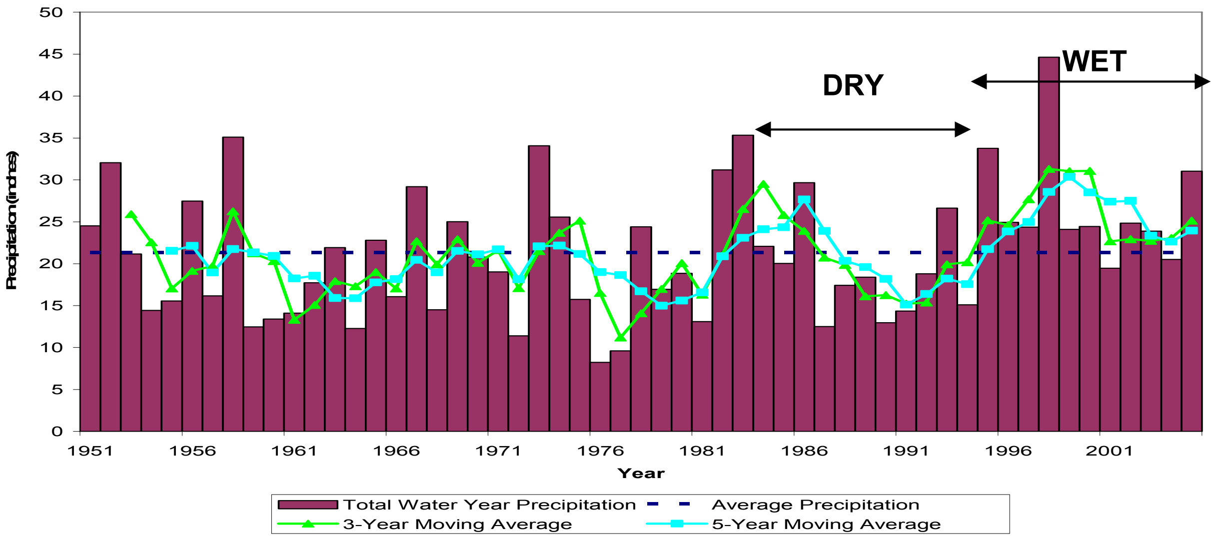

Figure 3.2 Historical Precipitation at San Francisco (Annual Totals - Inches)

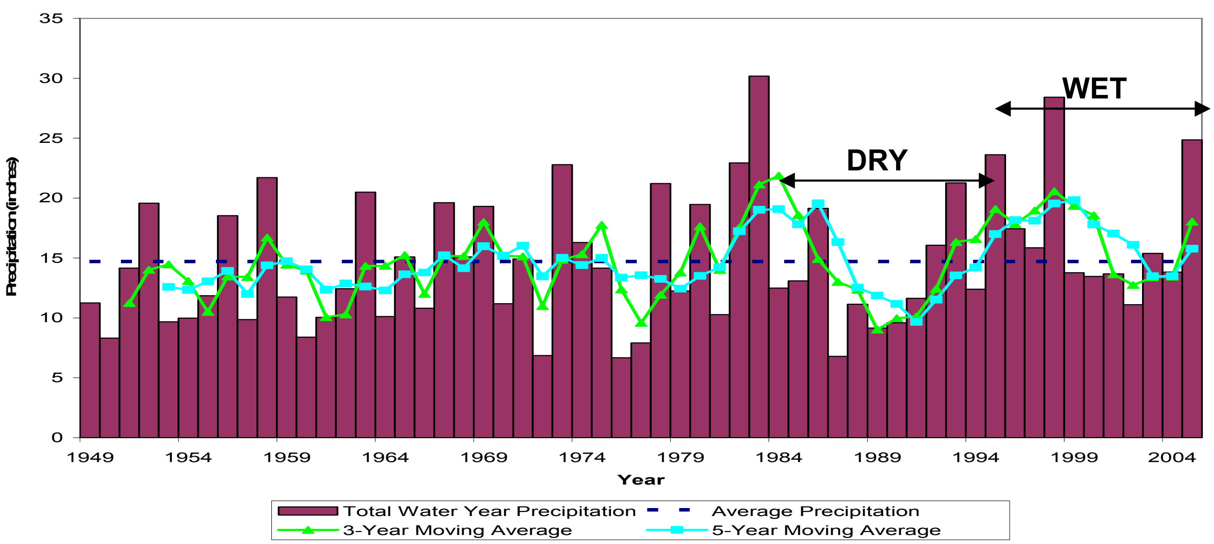

Figure 3.3 Historical Precipitation at San Jose (Annual Totals - Inches)

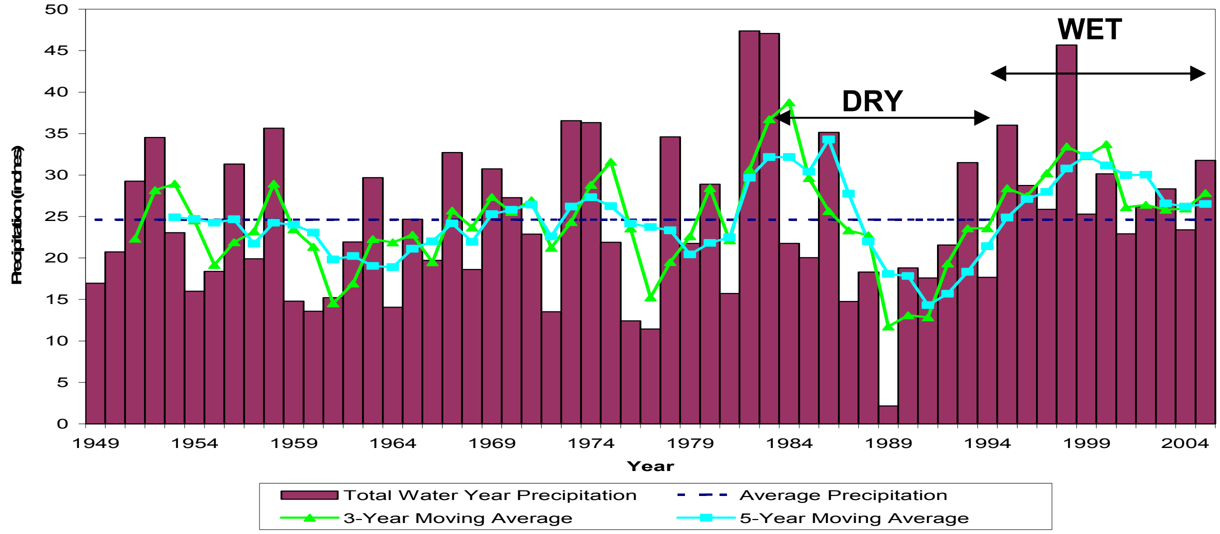

Figure 3.4 Historical Precipitation at Berkeley (Annual Totals - Inches)

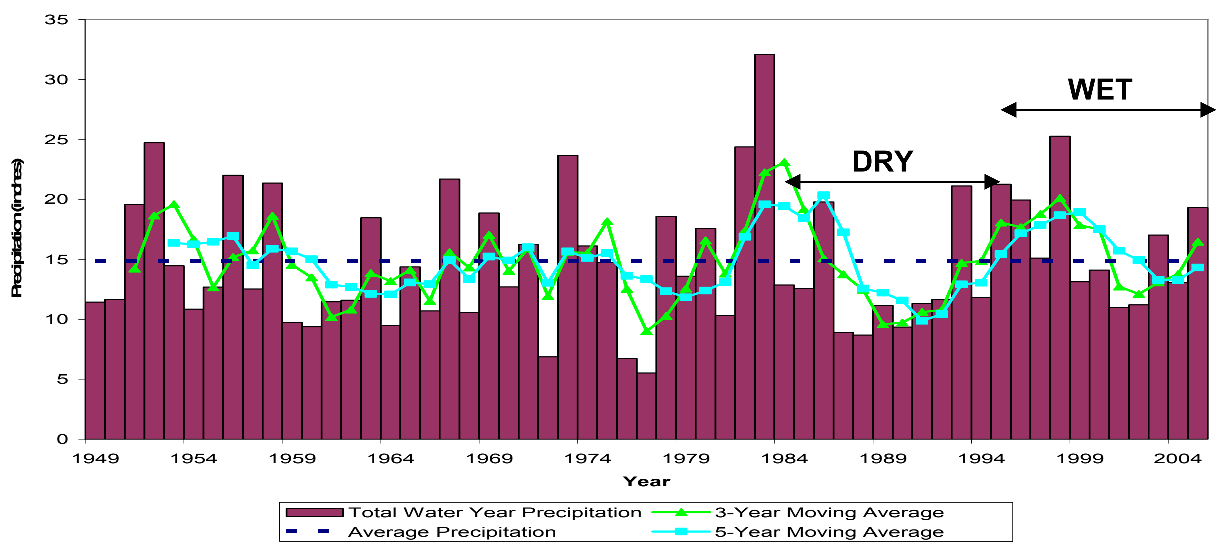

Figure 3.5 Historical Precipitation at Livermore (Annual Totals - Inches)

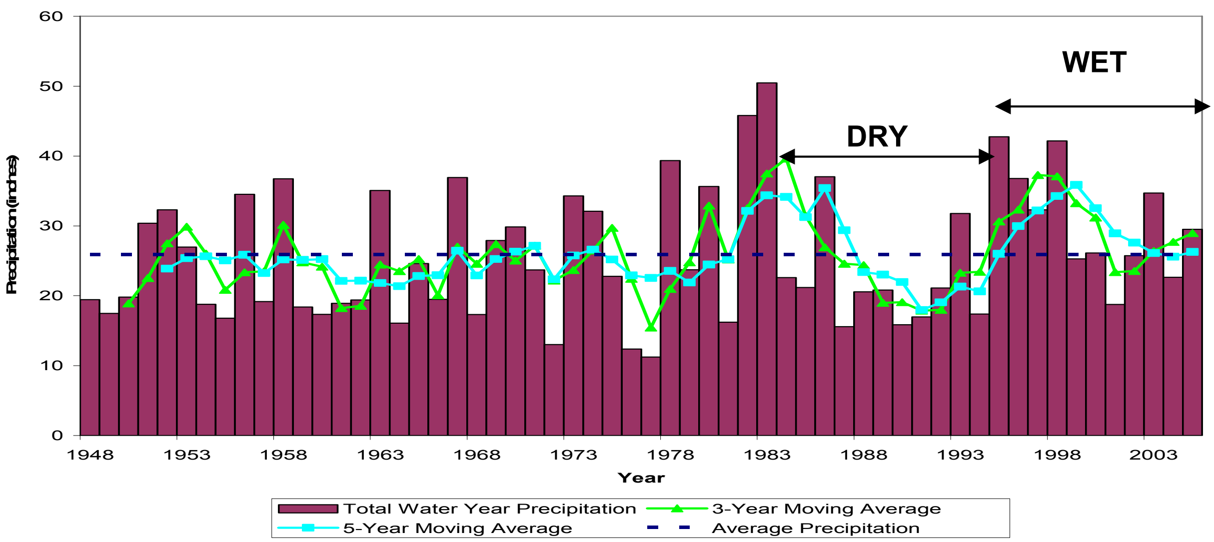

Figure 3.6 Historical Precipitation at Napa State Hospital (Annual Totals - Inches)

Based on these rainfall time series, the following scenarios were run:

a. The entire 26-year period, water year 1981 through water year 2005, starting with the 2005-ending conditions noted above. This provides a repeat of the historic time period and its associated climate conditions.
b. A Dry meteorological run using the 11-year period from 1984 to 1994, repeated for two or three cycles.
c. A Wet meteorological run using the 11-year period from 1995 to 2005, repeated for two or three cycles.

3.3 MODEL RESULTS AND DISCUSSION

The modeling described in this portion of the study was conducted in order to determine what response time in the environment could reasonably be expected following reductions in copper from brake sources. This response time was found by comparing a scenario where all brake sources are eliminated at once to a scenario where the brake sources are left unchanged (at the levels used for the Phase 1 modeling). It is important to note, however, that there is no year at which all the brake sources are expected to be eliminated at once. Instead, for example, if manufacturers reduce the use of copper in their brake formulations, a reduction in releases from brake sources to the environment would occur gradually as old brakes are replaced and new lower-copper formulations come on the market.

Upon completion of the model scenario runs, a series of analysis steps were performed in order to process the model output into a form for assessing the time lag demonstrated under the scenario where brake sources are eliminated. These steps involved the following:

1. Process the model output of each run to generate annual copper loads to the Bay for each of the test sub-watersheds.
2. Plot the annual loads for each of three scenarios. An example of these annual loads for the Santa Clara Valley Central sub-watershed is shown in Figure 3.7. This shows the **TOTAL** annual copper loads delivered to the bay from under the three scenarios of copper releases:

a. Brake Sources Unchanged – **BLUE** line (total loads from Phase 1 modeling)
b. Brake Sources Turned Off at Time = 0 – **RED** Line
c. Baseline – **GREEN** line (includes non-brake anthropogenic and background sediment sources but no brake sources)

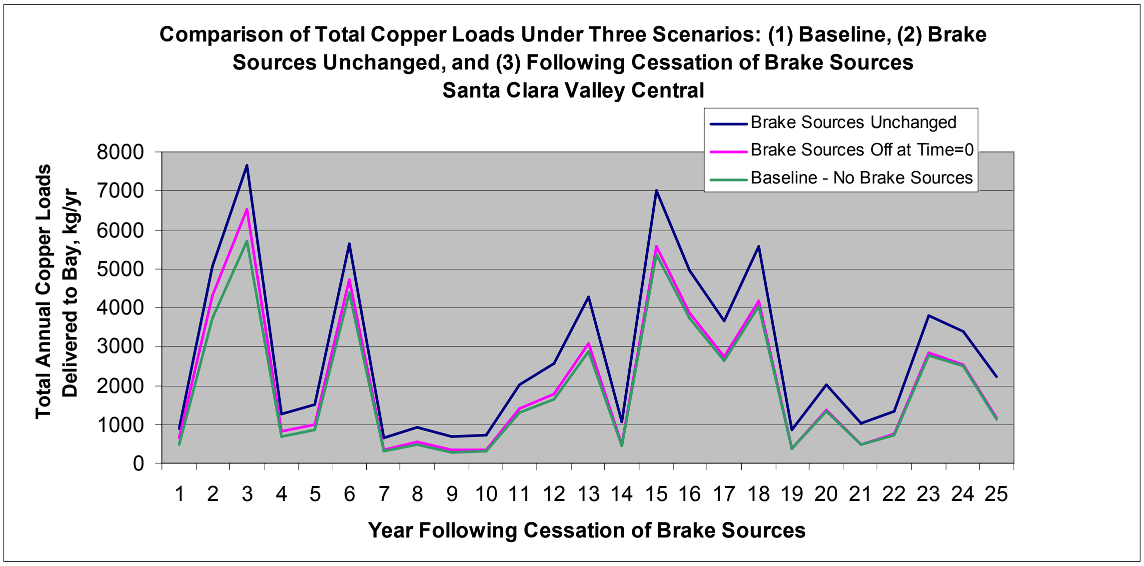

Figure 3.7 Comparison of Total Copper Loads When Brake Sources Are Unchanged, When Brake Sources Are Eliminated at Time = 0, and When There Are No Brake Sources

These loads are shown for a 25-year simulation period using the historical meteorological data for the water year 1981 through water year 2005 (water years extend from October to September). In the second scenario (**RED** Line), the simulation starts with initial copper conditions the same as the first scenario with the brake sources unchanged (**BLUE** line) and then the brake sources are turned off at the beginning of the simulation period. The resulting **RED** line gradually approaches the **GREEN** Line as the brake-derived contribution approaches zero, indicating that the annual copper loads are approaching baseline levels that include contributions from sediment and non-brake anthropogenic sources only.

In Figure 3.7, copper loads for year 1 for the “Brake Sources Unchanged” case are low compared to other years because year 1 was modeled with water year 1981 meteorological data. This was an extremely dry year with very little runoff, resulting in low copper loads. The changes from year to year for each loading scenario in this chart show how dramatically total copper loads to the San Francisco Bay vary in response to wet or dry precipitation years. Thus, it is the relative difference between the “Brake Sources Unchanged” and “Brake Sources Off at Time = 0” curves that provides information about the changes in copper loading from brake sources, not the absolute amount of the loading from one year to the next.

3. The next step involves calculating the annual contribution just from brake sources to quantify its reduction with time over the 25-year period after sources are turned off. This involves subtracting out the baseline load from the other two scenarios, i.e., subtracting the **GREEN** Line from both the **BLUE** line and the **RED** Line. Figure 3.8 shows the

resulting **annual brake-derived copper loads** for the two scenarios:

a. Brake Sources Unchanged – **BLUE** line (brake source loads from Phase 1 modeling)
b. Brake Sources Turned Off at Time = 0 – **RED** Line

Also shown in Figure 3.8 is the difference in loads between these two scenarios (the reduction in loads that is occurring because the brake sources were turned off). This is the **BLACK** line, i.e. the **BLUE** line minus the **RED** line.

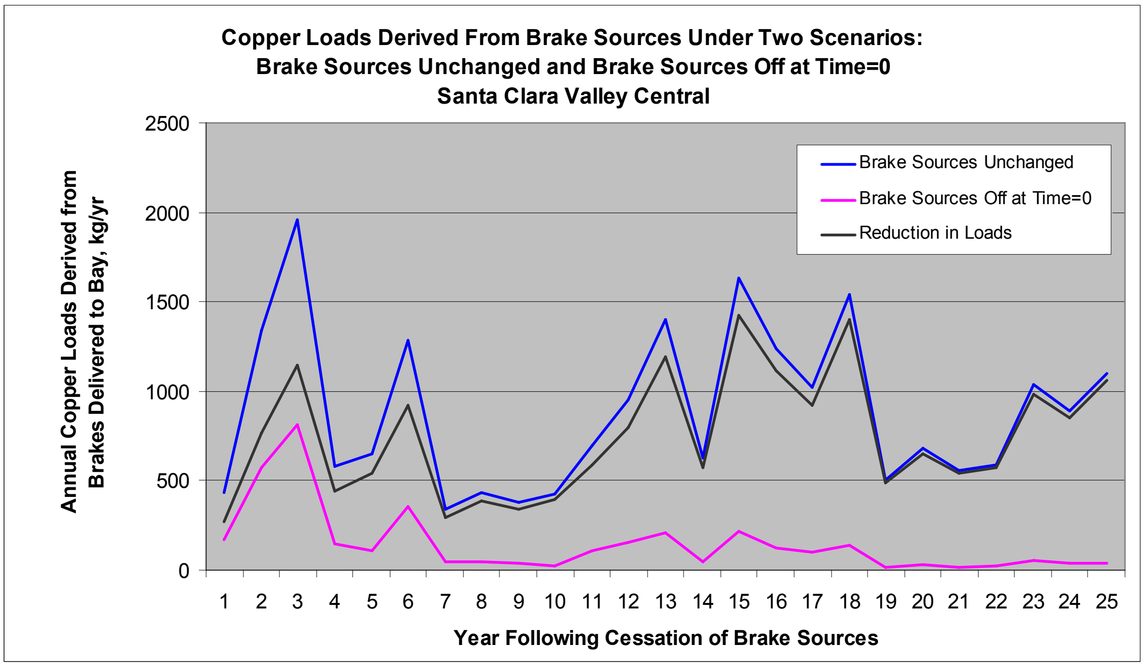

Figure 3.8 Copper Loads from Brake-Derived Sources When Brake Sources Are Unchanged and When Brake Sources Are Eliminated at Time = 0

The brake-derived loads approach zero with time once they have been turned off (**RED** line), and the annual reduction (**BLACK** line) converges with the unchanged brake source loads (**BLUE** line).

4. The final step is to express the reduction in brake-derived loads following the cessation of brake sources over the 25-year period as a percent reduction. This percent reduction gives the time lag, or how long it takes to reduce brake-derived loads by some percentage of the loads when the brake sources are unchanged. This percent reduction is calculated by taking the ratio of the **RED** line to the **BLUE** line (in Figure 3.8). The left axis of Figure 3.9 shows the results of this calculation as the curve of the annual percent reduction from loads that would have been observed had brake sources remain unchanged over the 25-year simulation period, instead of ceasing at time = 0. For the Santa Clara Valley Central sub-watershed, the curve crosses 80% six or seven years after brake sources of copper cease. The right axis on this graph represents the percent of the loads that would have been delivered to the Bay had brake sources remained unchanged instead of ceasing at time = 0. It is simply calculated as 100%

minus the percent reduction values on the left-hand scale; it approaches 0% with time following the cessation of the brake sources.

In summary, the **left axis** is used to answer the question:

"If ALL brake sources of copper are eliminated, how long will it take to achieve an 80% reduction in the annual brake-derived loads?"

The **right axis** is used to answer the question:

"If ALL brake sources of copper are eliminated, how long will it take for annual brake-derived loads to reach 20% of the levels they would have been if brake sources were unchanged?"

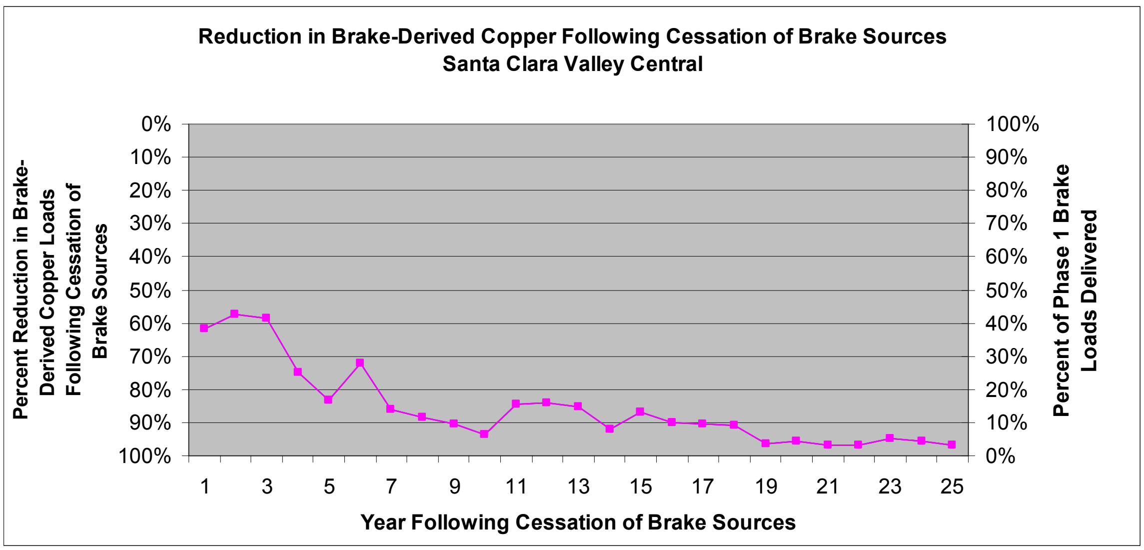

Figure 3.9 Percent Reduction in Brake-Derived Copper Loads Following Cessation of Brake Sources at Time=0

FIGURE 3.10 shows the same numbers as Figure 3.9 except it is in the form of a bar graph, and it also includes the five-year moving average of the load reductions. The left and right scales are interpreted in the same fashion as discussed above for Figure 3.9. The moving average is plotted at the midpoint of the five-year time periods; it tends to smooth out the year-to-year fluctuations that are due to meteorologic conditions, and provides a better representation of the reduction in brake-derived loads with time.

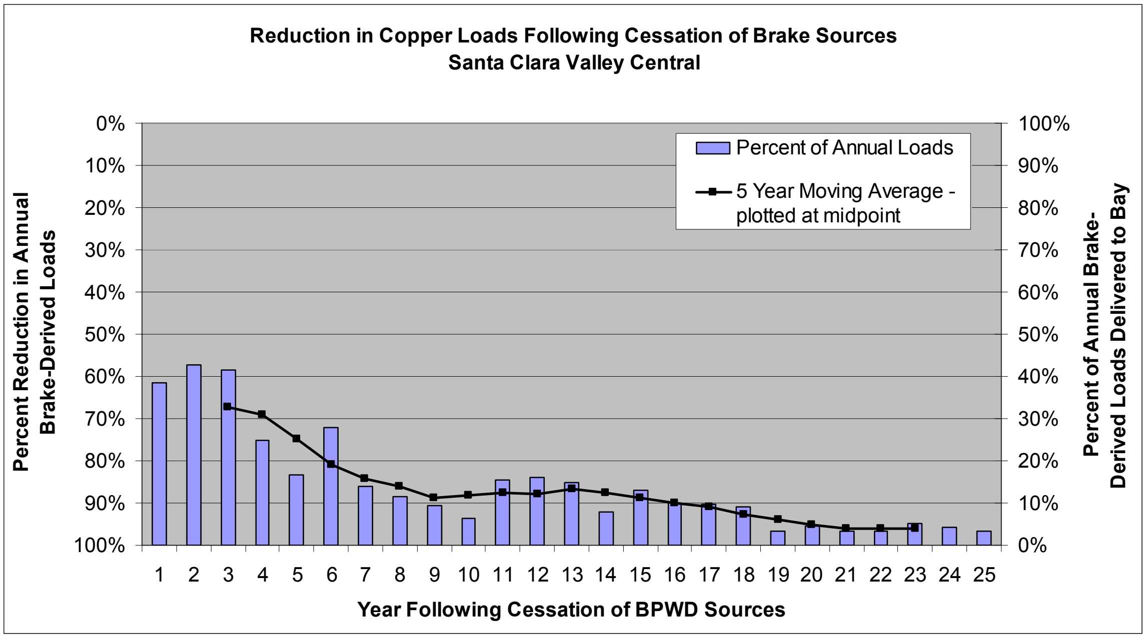

Figure 3.10 Percent Reduction in Brake-Derived Copper Loads Following Cessation of Brake Sources at Time=0

Figure 3.10 shows the format in which the model results for the lag-time assessment are presented for all the remaining sub-watersheds.

3.3.1 Model Results for the Five Sub-Watersheds

The results of the 15 scenarios, (i.e., the three meteorological scenarios for each of the five example sub-watersheds) are shown in the following plots (Figures 3.11-3.25), where the metric described above is plotted as a function of time. As discussed above, these plots portray the time it takes for the brake-derived copper sequestered in the soil and stream bed sediments to be removed by wash-off, in the case of soil, and desorption/scour, in the case of stream sediments. The resulting copper load reductions to the Bay in the first year range from 60% in Santa Clara Valley Central to 90% In East Bay North. However, these annual reductions through time are highly variable and dependent on annual meteorological conditions, primarily precipitation and runoff. For the Historical Meteorological Scenario, the East Bay North and Santa Clara Valley Central reductions fluctuate up and down depending on the total copper load, which is highly dependent on rainfall. In the other three sub-watersheds (Petaluma, Peninsula Central, Upper Colma), the downward trend is more consistent. The fluctuation is generally more pronounced, and somewhat more extended in time, in the Dry meteorological scenario, and less pronounced, and shows a faster rate of reduction, in the Wet scenario.

The results of these runs are summarized by compiling the time it takes to reach selected percentages of the brake portion of the copper loads that were estimated during the Phase 1 modeling, e.g. 5%, 10% or 20% of the Phase 1 brake loads; these percentages also correspond to 95%, 90%, and 80% reductions in the brake loads. Table 3.1 shows the times required to reach each of these levels based on 5-year increments, i.e., 0-5, 6-10, etc. As shown in these results, meteorology has an effect on the time it takes to reach 5% of the Baseline loads, but the effect is small especially for the 90% and 80% reductions levels. However, for the 95% reduction level, the Petaluma and Santa Clara Valley Central sub-watersheds demonstrate shorter times for the wet scenario, and the Peninsula and Santa Clara Valley Central sub-watersheds show longer times for the dry scenario. In short, brake contributions will be reduced by 80% within 5 years for most sub-watersheds, but possibly up to 10 years in others. To reach a 95% reduction level, two decades or more may be required. Also, the results suggest that the length of the stream channel in each sub-watershed, plus the copper deposition loading might be having an effect on the time it takes to reach the Baseline loads. The Santa Clara Valley Central sub-watershed has the longest modeled stream channel, and is also a relatively urban watershed. The Petaluma sub-watershed has a long stream channel, but substantially less brake copper deposition.

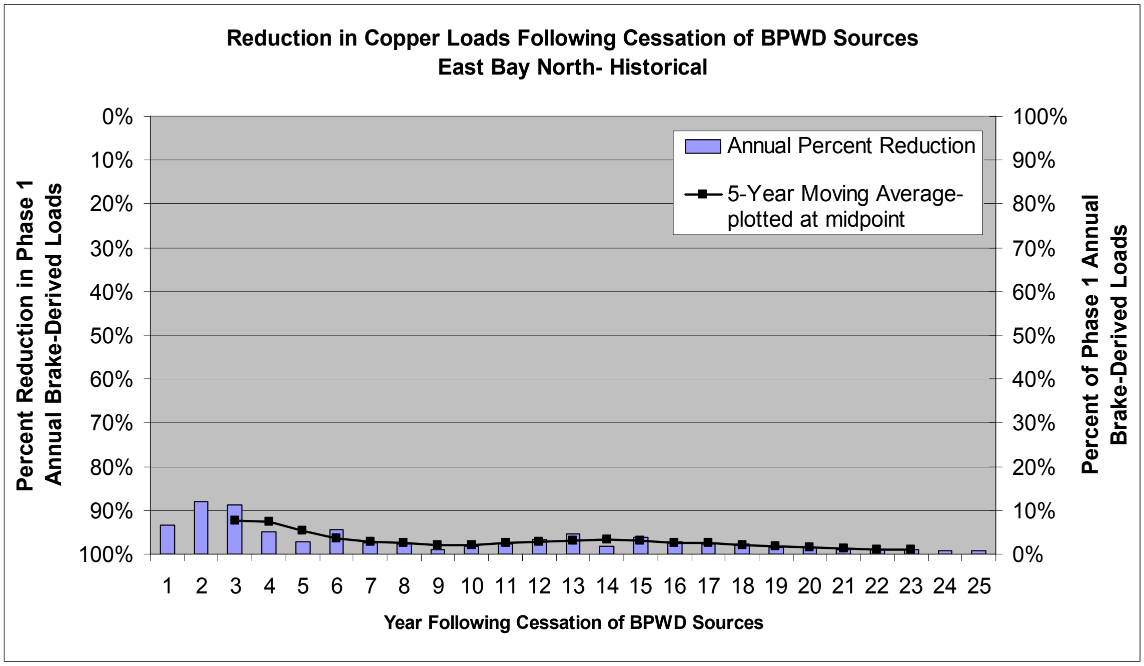

Figure 3.11 Reduction in Copper Loads Following Cessation of Brake Sources in East Bay North Under Historical Meteorological Conditions

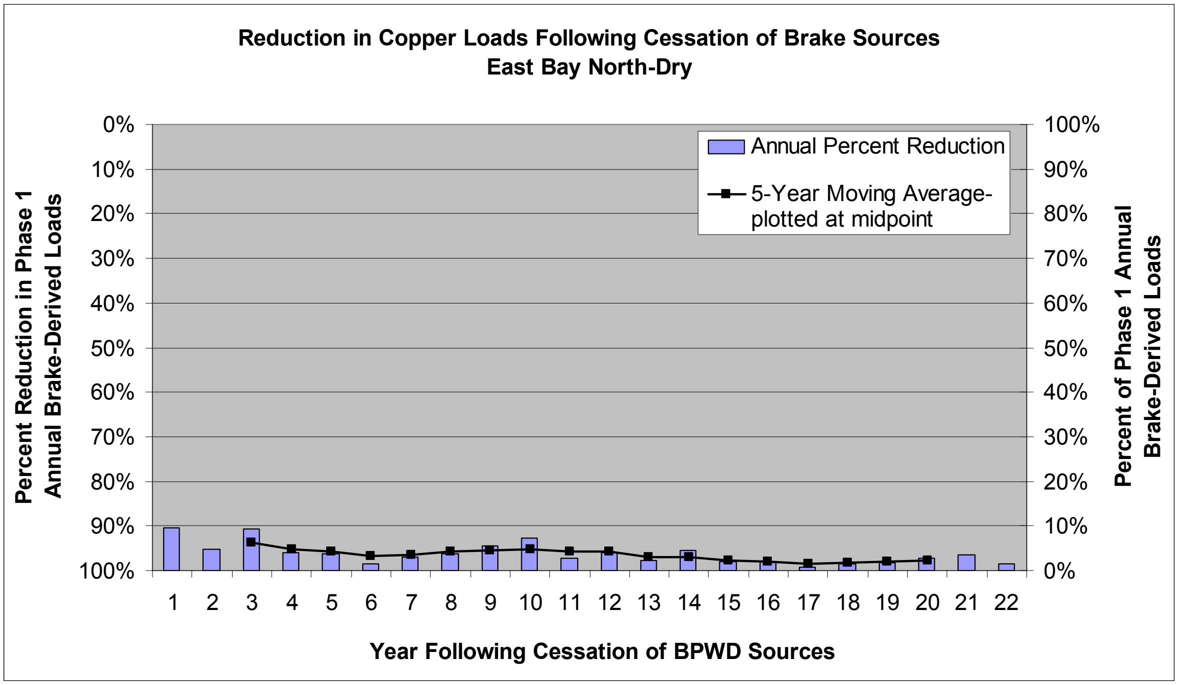

Figure 3.12 Reduction in Copper Loads Following Cessation of Brake Sources in East Bay North Under Dry Meteorological Conditions

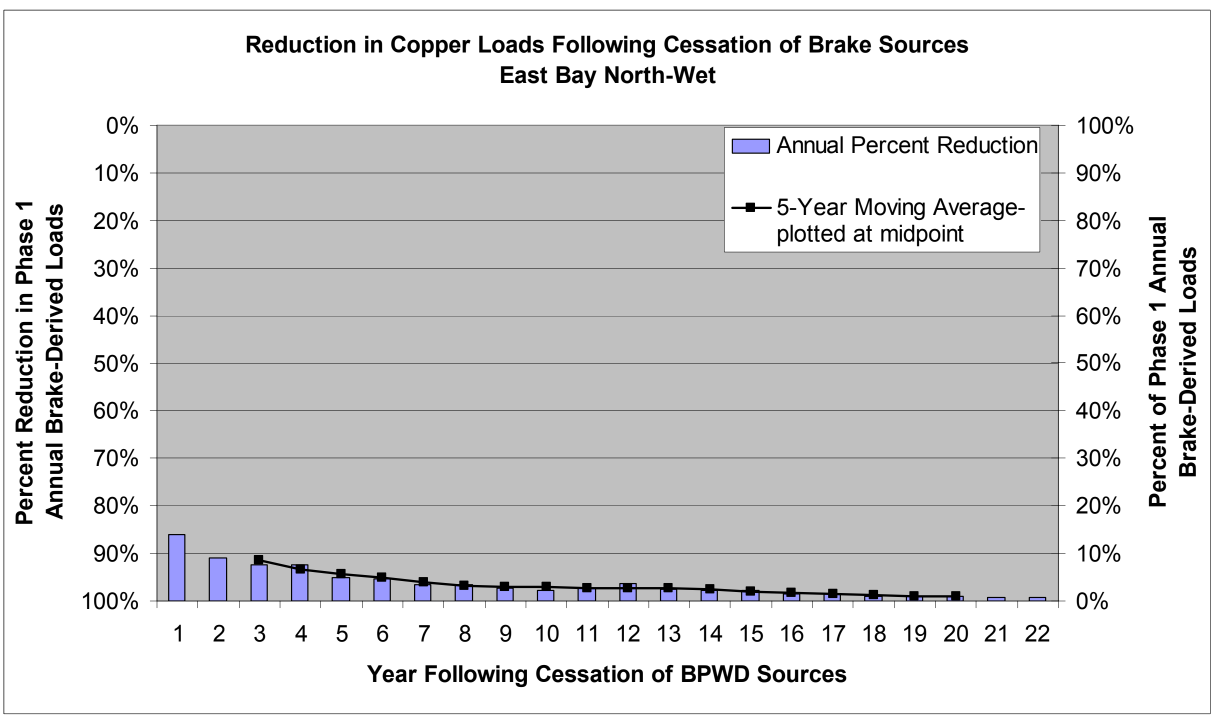

Figure 3.13 Reduction in Copper Loads Following Cessation of Brake Sources in East Bay North Under Wet Meteorological Conditions

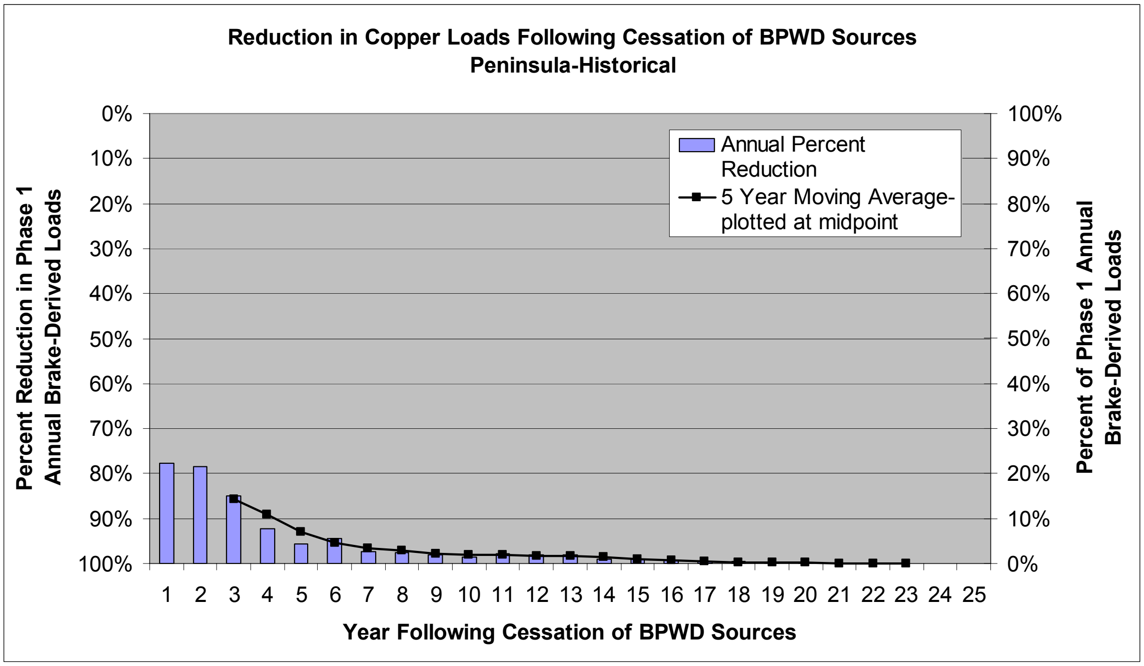

Figure 3.14 Reduction in Copper Loads Following Cessation of Brake Sources in Peninsula Central Under Historical Meteorological Conditions

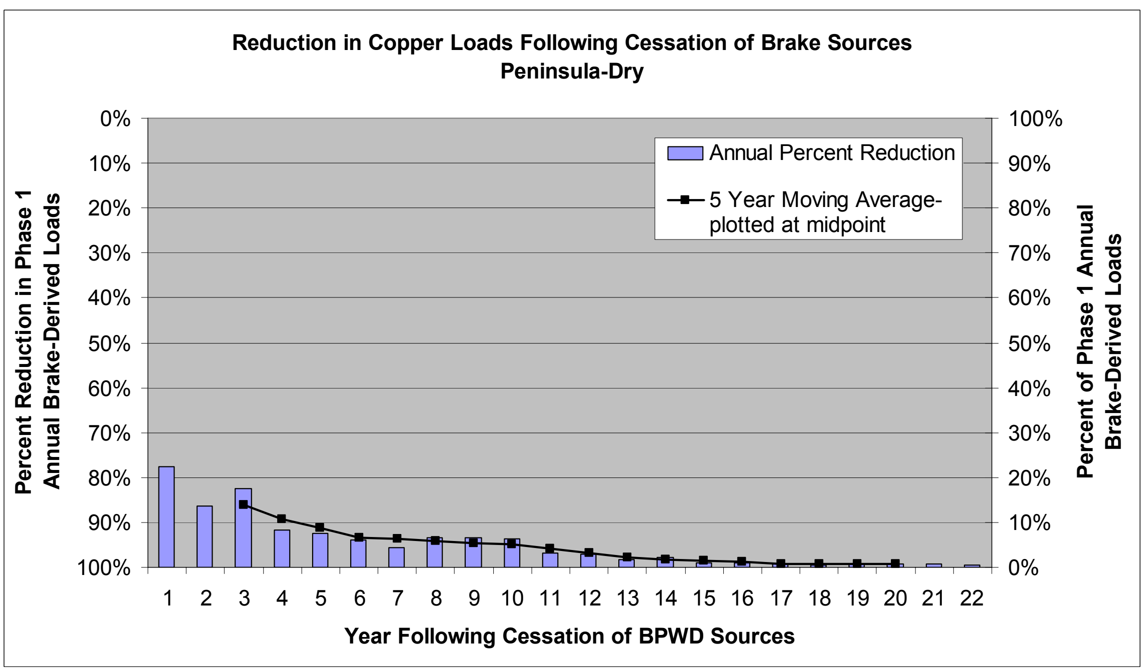

Figure 3.15 Reduction in Copper Loads Following Cessation of Brake Sources in Peninsula Central Under Dry Meteorological Conditions

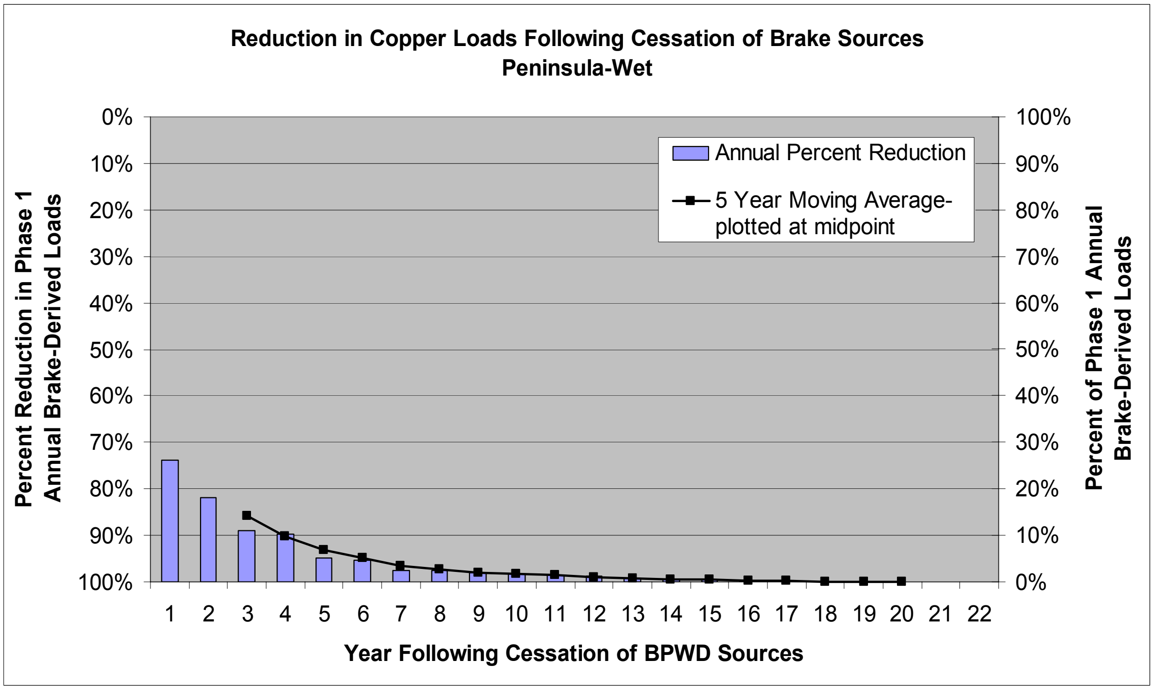

Figure 3.16 Reduction in Copper Loads Following Cessation of Brake Sources in Peninsula Central Under Wet Meteorological Conditions

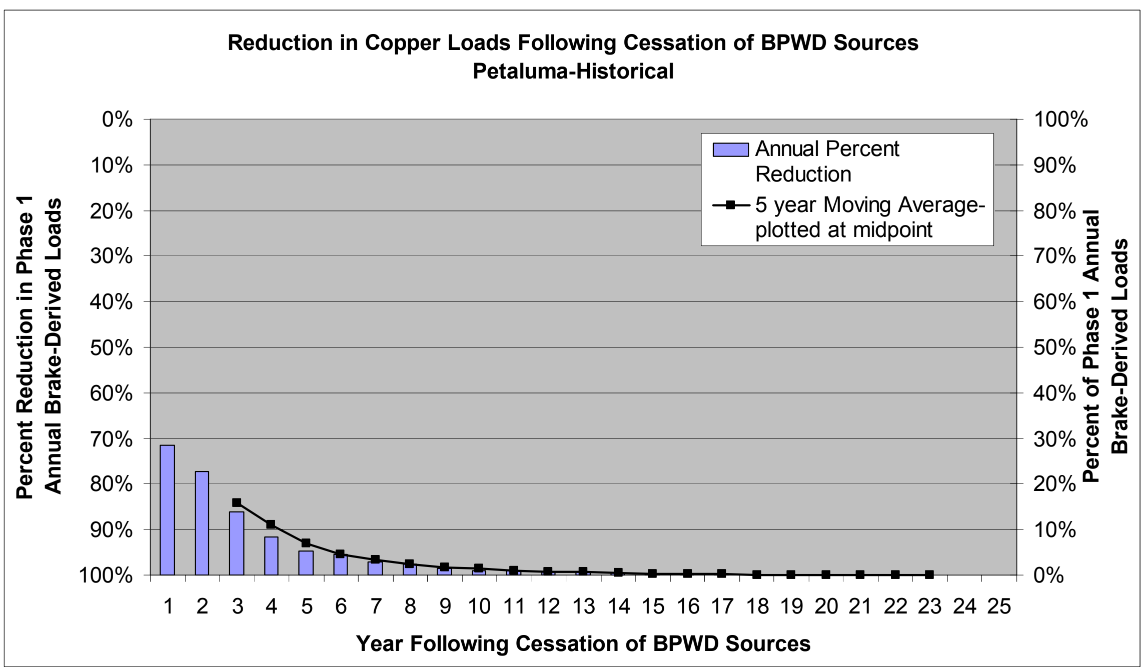

Figure 3.17 Reduction in Copper Loads Following Cessation of Brake Sources in Petaluma Under Historical Meteorological Conditions

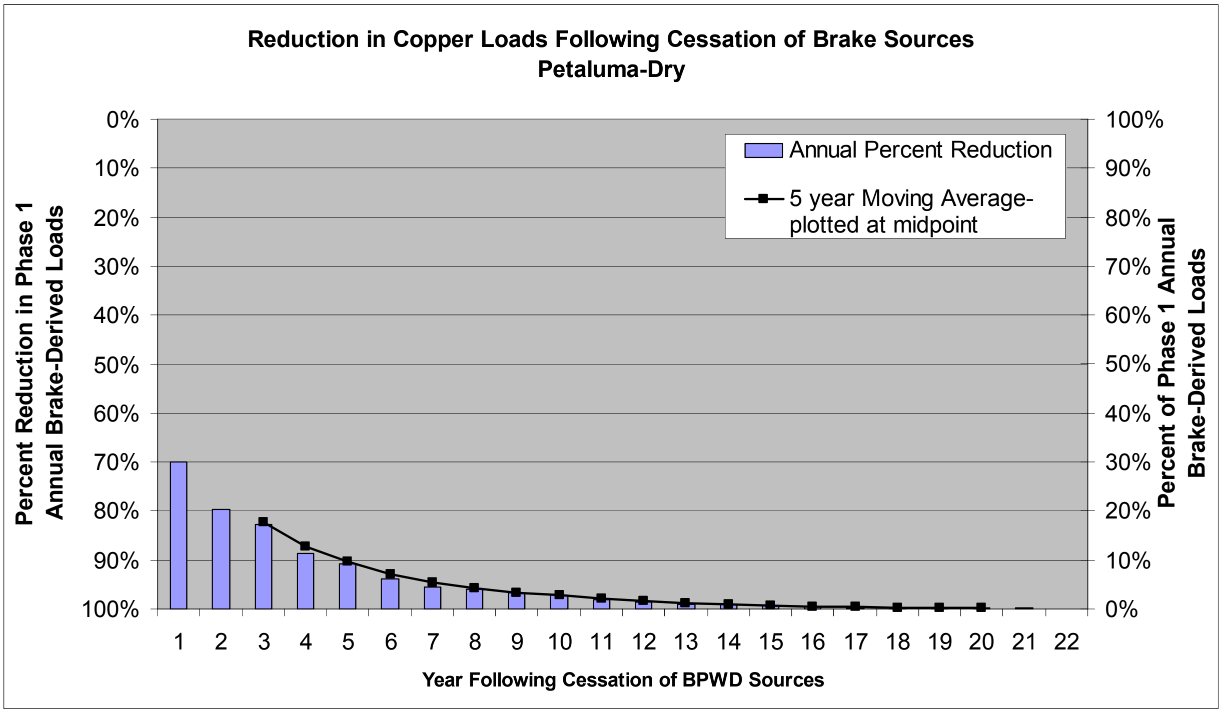

Figure 3.18 Reduction in Copper Loads Following Cessation of Brake Sources in Petaluma Under Dry Meteorological Conditions

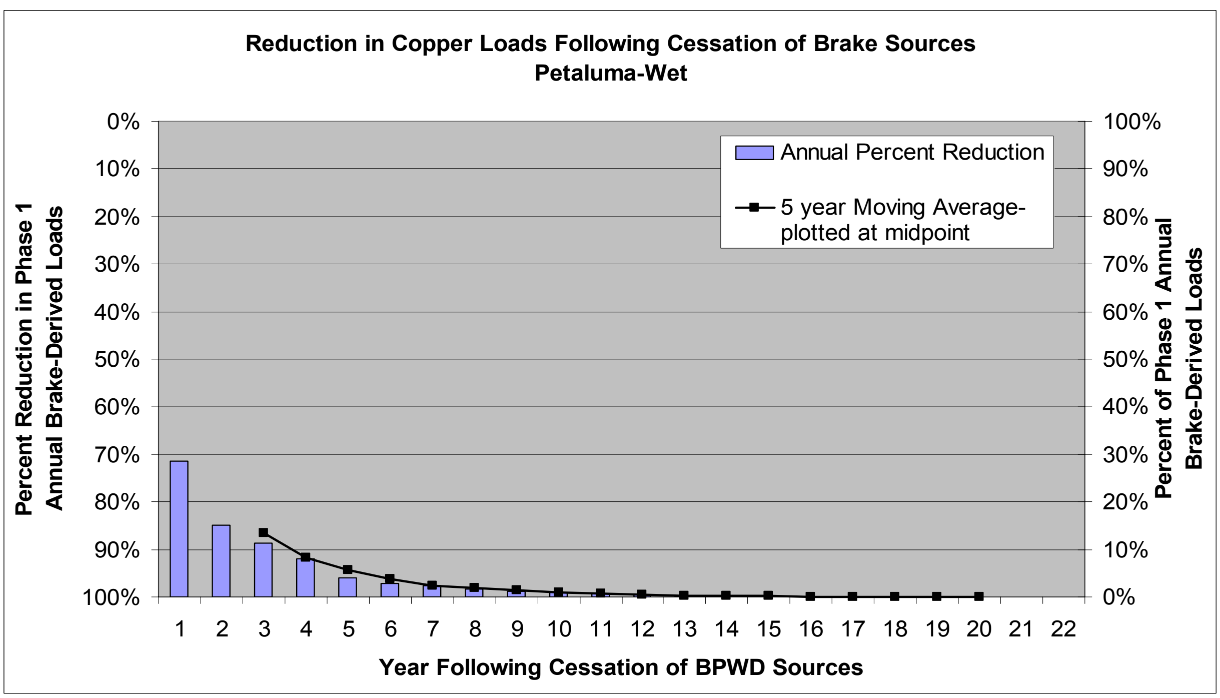

Figure 3.19 Reduction in Copper Loads Following Cessation of Brake Sources in Petaluma Under Wet Meteorological Conditions

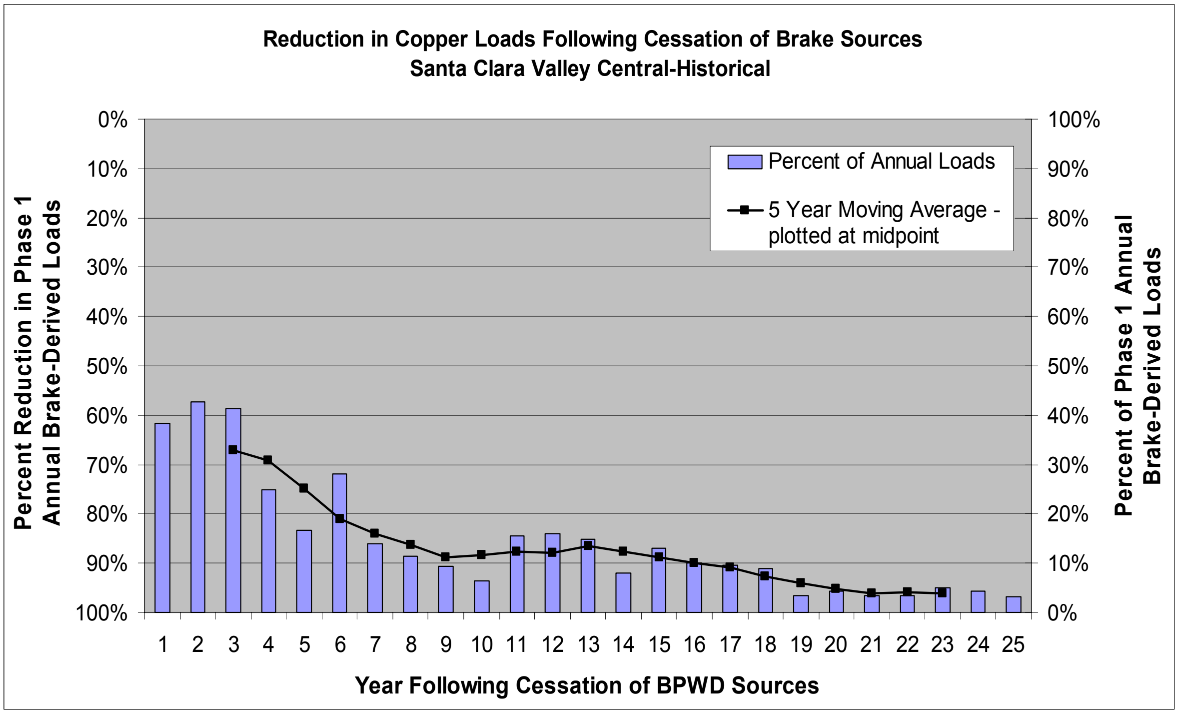

Figure 3.20 Reduction in Copper Loads Following Cessation of Brake Sources in Santa Clara Valley Central Under Historical Meteorological Conditions

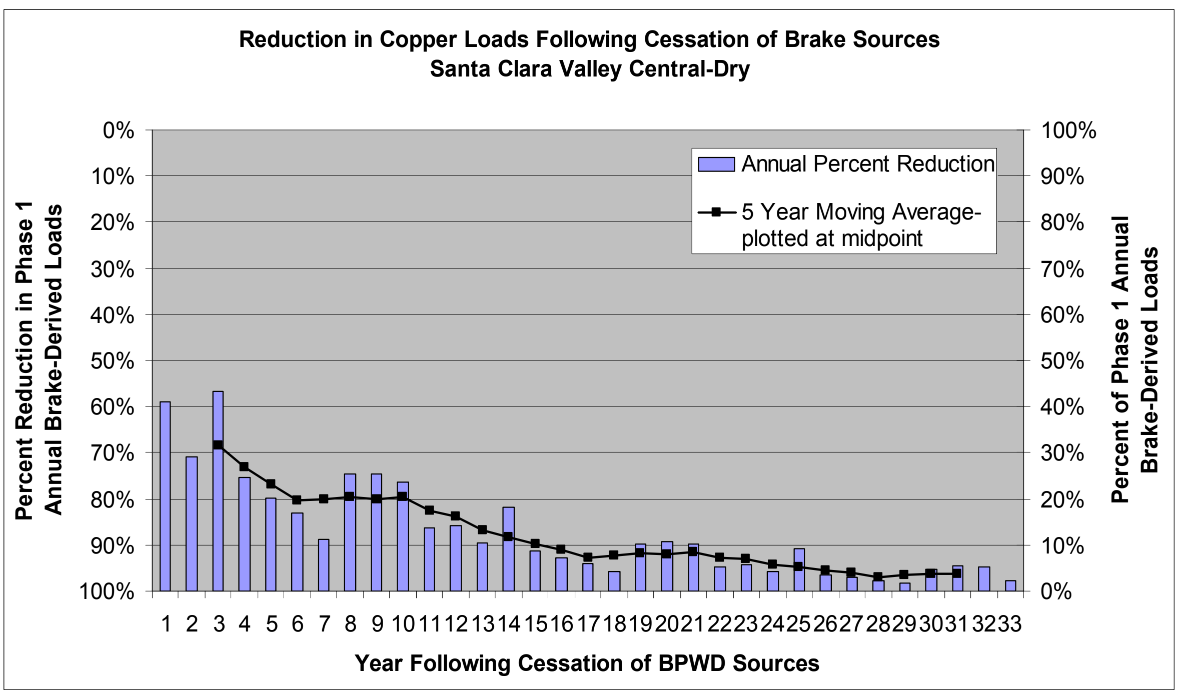

Figure 3.21 Reduction in Copper Loads Following Cessation of Brake Sources in Santa Clara Valley Central Under Dry Meteorological Conditions

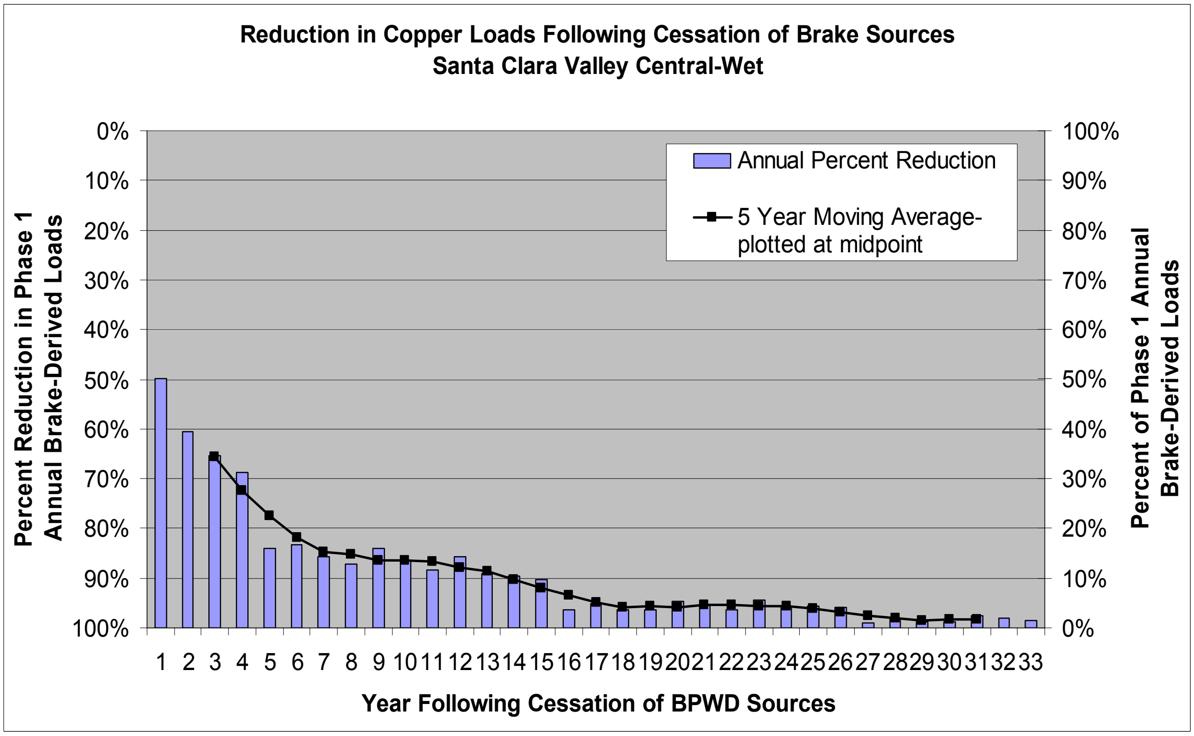

Figure 3.22 Reduction in Copper Loads Following Cessation of Brake Sources in Santa Clara Valley Central Under Wet Meteorological Conditions

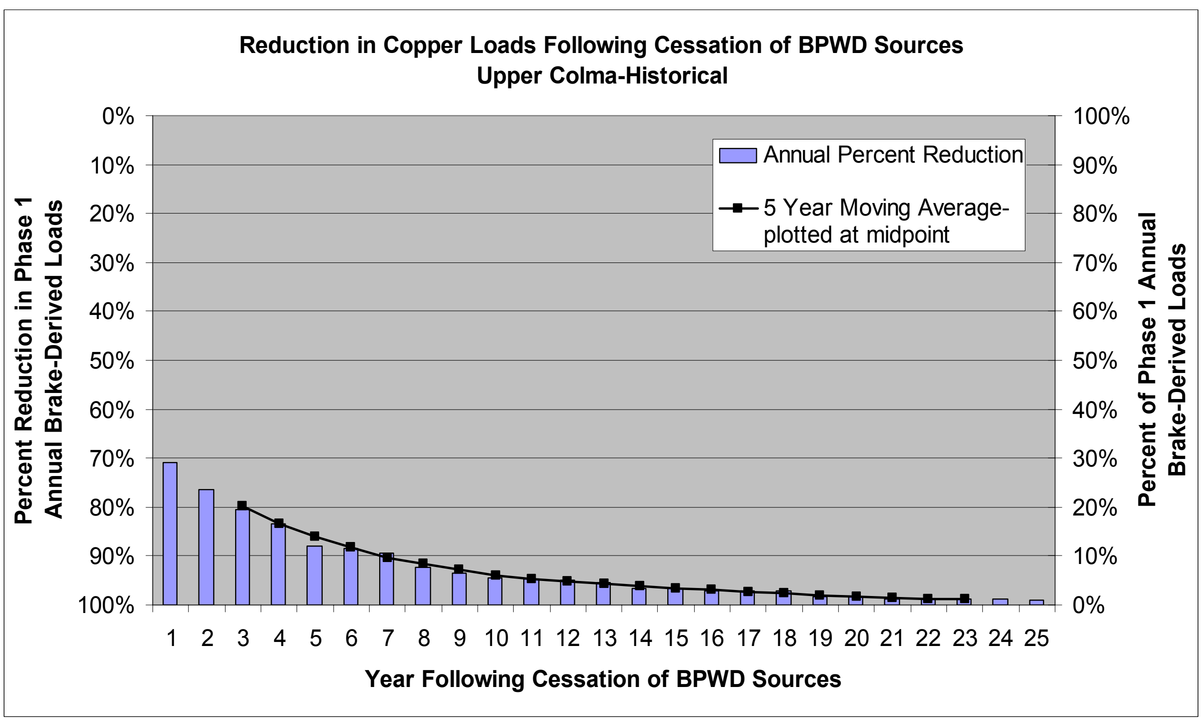

Figure 3.23 Reduction in Copper Loads Following Cessation of Brake Sources in Upper Colma Under Historical Meteorological Conditions

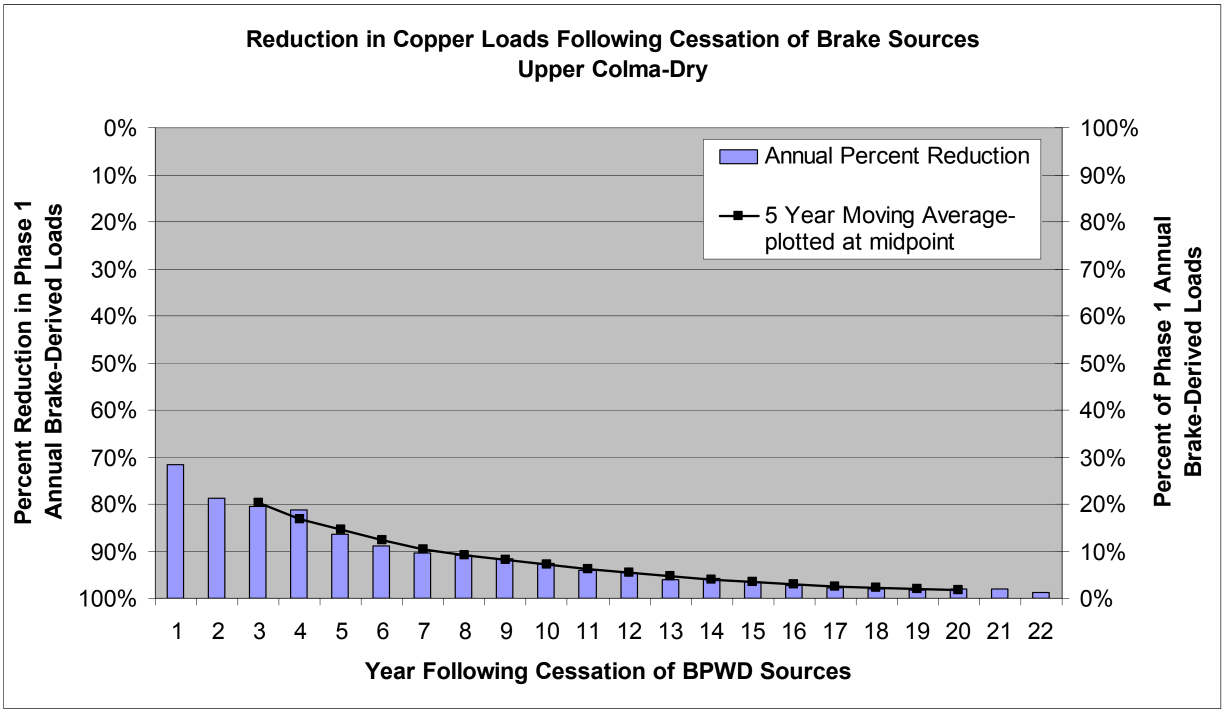

Figure 3.24 Reduction in Copper Loads Following Cessation of Brake Sources in Upper Colma Under Dry Meteorological Conditions

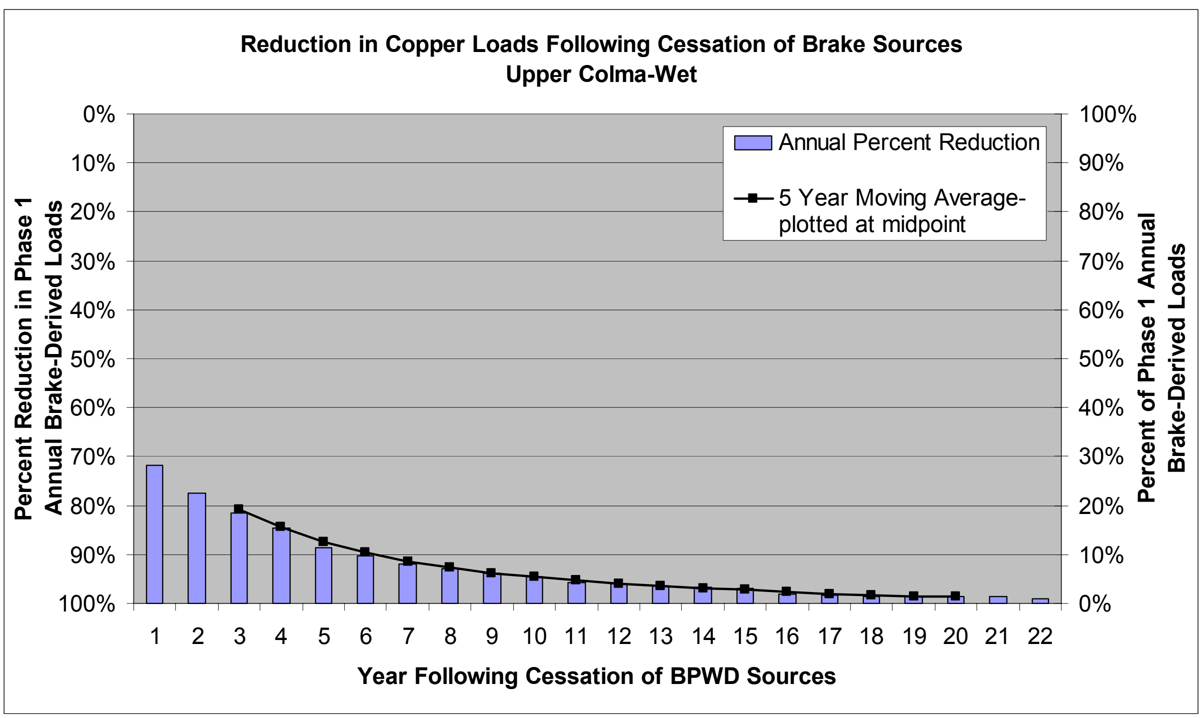

Figure 3.25 Reduction in Copper Loads Following Cessation of Brake Sources in Upper Colma Under Wet Meteorological Conditions

Table 3.1 Time to Reach 5%, 10%, and 20% of Brake Copper Loads (Years)

	Time Lag to Reach 5% of Brake Copper Loads (years), 95% Reduction in Brake Loads				
	Historical Met Data, WY84-WY05		Dry Scenario, WY84-WY94		Wet Scenario, WY95-WY05
East Bay North	6 - 10		6 - 10		6 - 10
Peninsula Central	6 - 10		10 - 15		6 - 10
Petaluma	6 - 10		6 - 10		0 - 5
Santa Clara Valley Central	>20		>25		16 - 20
Upper Colma	11 - 15		11 - 15		11 - 15

	Time Lag to Reach 10% of Brake Copper Loads (years), 90% Reduction in Brake Loads				
	Historical Met Data, WY84-WY05		Dry Scenario, WY84-WY94		Wet Scenario, WY95-WY05
East Bay North	0 - 5		0 - 5		0 - 5
Peninsula Central	0 - 5		0 - 5		0 - 5
Petaluma	0 - 5		0 - 5		0 - 5
Santa Clara Valley Central	16 - 20		16 - 20		11 - 15
Upper Colma	6 - 10		6 - 10		6 - 10

	Time Lag to Reach 20% of Brake Copper Loads (years), 80% Reduction in Brake Loads				
	Historical Met Data, WY84-WY05		Dry Scenario, WY84-WY94		Wet Scenario, WY95-WY05
East Bay North	0 - 5		0 - 5		0 - 5
Peninsula Central	0 - 5		0 - 5		0 - 5
Petaluma	0 - 5		0 - 5		0 - 5
Santa Clara Valley Central	6 - 10		6 - 10		6 - 10
Upper Colma	0 - 5		0 - 5		0 - 5

SECTION 4.0

CONCLUSIONS

Because of the way the buildup and washoff fractions on impervious surfaces were handled in the Phase 1 modeling, concern was raised that the relative contribution of copper from brake pad wear debris to total copper in runoff to the San Francisco Bay might be understated. In this Phase 2 modeling, copper that was “lost” in the buildup and washoff functions in the Phase 1 modeling is modeled as if it were applied to 10 m wide roadside buffers. Results for both 100% impervious and 100% pervious buffers were presented. A subset of the sub-watersheds in the San Francisco Bay watershed that represent the range of land use covers in the watershed were studied.

The absolute increase in the relative contribution of copper from brake pad wear debris using Phase 2 results is an estimated 1 to 2% higher if the roadside buffer is assumed to be 100% pervious, and 8 to 17% higher if the roadside buffer is assumed to be 100% impervious. The largest increases for the 100% impervious case are seen in the least urbanized sub-watersheds, where roadway adjacent land has less likelihood of being impervious than in the other sub-watersheds.

The most urbanized sub-watersheds in the Phase 2 study, based on the fraction of the sub-watershed land cover that is impervious, are the Upper Colma and East Bay North sub-watersheds. In the Phase 1 study, the estimated relative contribution of copper from brake pads was 50% in the Upper Colma sub-watershed, while Phase 2 estimates are 52% (for 100% pervious buffer) and 60% (for 100% impervious buffer). In the East Bay North sub-watershed, the Phase 1 result was 36%, while the Phase 2 estimates are 38% and 44%.

Phase 2 modeling indicates that the length of time it will take copper to wash out of the San Francisco Bay watersheds once release reduction measures are in place is not largely influenced by the weather patterns that occur at the time of the reduction measures. Modeling results indicated that if sources of brake pad copper are eliminated, 90% of brake pad contributions to runoff will be eliminated in five years or less in three of the five modeled sub-watersheds (East Bay North, Peninsula Central, and Petaluma sub-watersheds). In the Santa Clara Valley Central sub-watershed, 90% of brake pad contributions will be eliminated within 11-20 years of the cessation of brake pad sources of copper, and in the Upper Colma sub-watershed, 90% of brake pad contributions will be eliminated within 6-10 years of the cessation of brake sources of copper.

SECTION 5.0

RECOMMENDATIONS FOR FURTHER MODELING

During this Phase 2 modeling, the biggest impacts on copper loading rates from brake debris were demonstrated to result from impervious buffers along roadways and higher accumulation limits (i.e., SQOLIM in HSPF). In addition, the time lag assessment was based on the median estimate scenario from Phase 1. With increased loadings, time lags are likely to increase. Additional modeling scenarios that may be of interest in assessing the changes in the expected time lags under the following conditions are:

1. Use of Phase 1 High-Brakes scenario loadings in place of the median estimate values
2. Use of Impervious buffers to receive the copper 'loss' due to the Phase 1 buildup/washoff modeling technique
3. Use of higher accumulation limits, if justified by minimal changes to the model calibration
4. Reasonable combinations of the above scenarios, as potential worst-case conditions

In addition, a number of the recommendations for model improvements from the Phase 1 report should be considered for further investigation. The major modeling recommendations would include: further calibration and validation with local watershed data, investigation of scour/deposition of copper in the streams connecting to the Bay, impacts of the reservoir representation, and more formal rigorous uncertainty analyses of model results.

SECTION 6.0

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