

Watershed Modeling of Copper Runoff to San Francisco Bay from Brake Pad Wear Debris

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ABSTRACT

This watershed modeling effort was conducted as part of a larger study by the Brake Pad Partnership (BPP) that examines the potential impact of copper from brake pad wear debris (BPWD) released to the environment in the San Francisco Bay (SF) Region. The watershed model provides runoff loads to a Bay modeling effort to assess resulting concentrations in SF Bay.

The U.S. EPA's Hydrological Simulation Program-FORTRAN (HSPF) model was set up for each of the 22 BPP modeled sub-watersheds that drain to the SF Bay. HSPF model runs were performed for each sub-watershed for the entire time period of water year 1981 through water year 2005. Model results were processed for flow, sediment, and copper loads; and annual and mean annual loads were tabulated.

Uncertainty in both non-brake and brake release estimates was assessed by representing alternative scenarios of source loadings. Three cases of copper release scenarios were modeled -- with high, low, and median releases. Each of these three scenarios was modeled with and without releases from brake pads in order to determine the relative contribution of copper from brake pads in runoff to the Bay.

The total anthropogenic contribution from brake pad wear debris towards total loads of copper to the Bay for the median estimate case varies from 15% to 57%. As expected, the brake pad contribution is much lower for the rural sub-watersheds than for the heavily urbanized sub-watersheds, reflecting alternative human activity and traffic levels.

Additional scenario runs were performed to assess the impacts of copper lost through the normal buildup/washoff attenuation algorithms and the time period for copper loads to return to background levels if all sources were eliminated. Scenario runs also considered impacts of climate changes such as wet and dry periods, and the relative impacts on loadings.

KEYWORDS

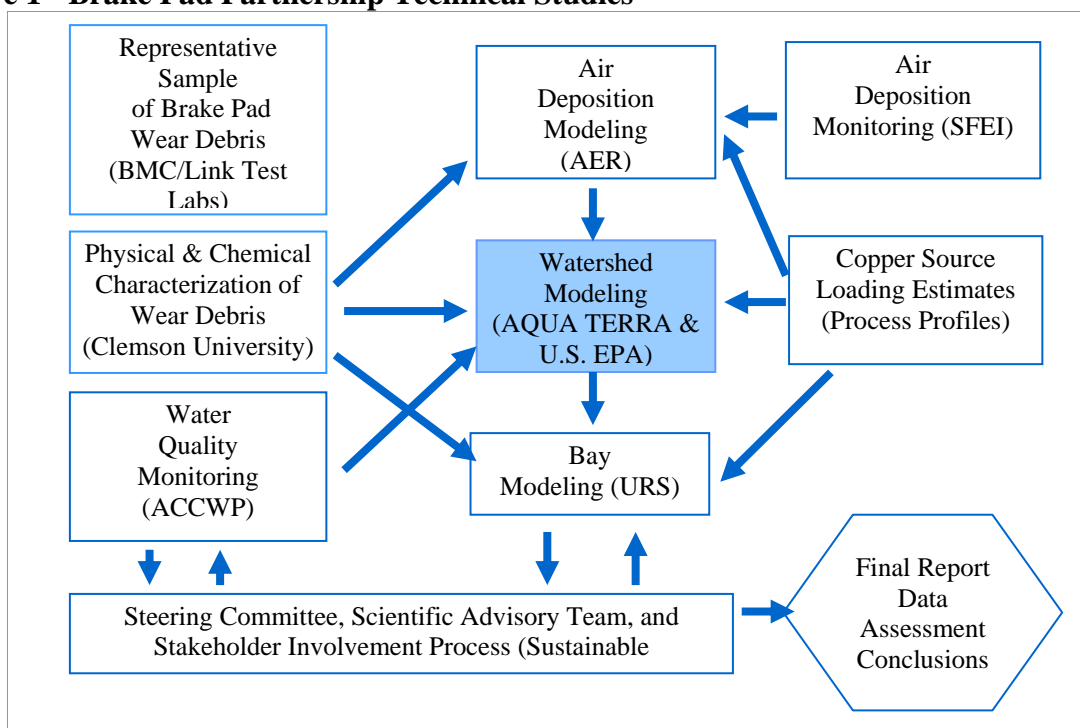
Watershed modeling, copper, water quality

INTRODUCTION

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 brake pads in stormwater discharges, the Partnership is translating its findings into control measures that would ensure reductions in copper from brake pads entering stormwater runoff. The Brake Pad Partnership has conducted a series of interconnected technical studies (Figure 1) to understand the role copper in automotive brake pads plays in contributing to copper levels in surface waters, using the San Francisco Bay as an example. The first objective of this study, Phase I (Donigian and Bicknell, 2007), is to predict through source inventories and fate/transport modeling using the Hydrological Simulation Program-FORTRAN (HSPF), the relative contribution of copper released from brake pads in the Bay area and how the contribution from brake pads affects both the short-term and long-term concentrations of copper in the Bay. The second objective, Phase II (Donigian et al., 2009), is to then adjust the model to better represent copper deposition on roadways and determine the time required for copper to return to baseline, or near baseline concentrations if the source is eliminated.

Figure 1 - Brake Pad Partnership Technical Studies



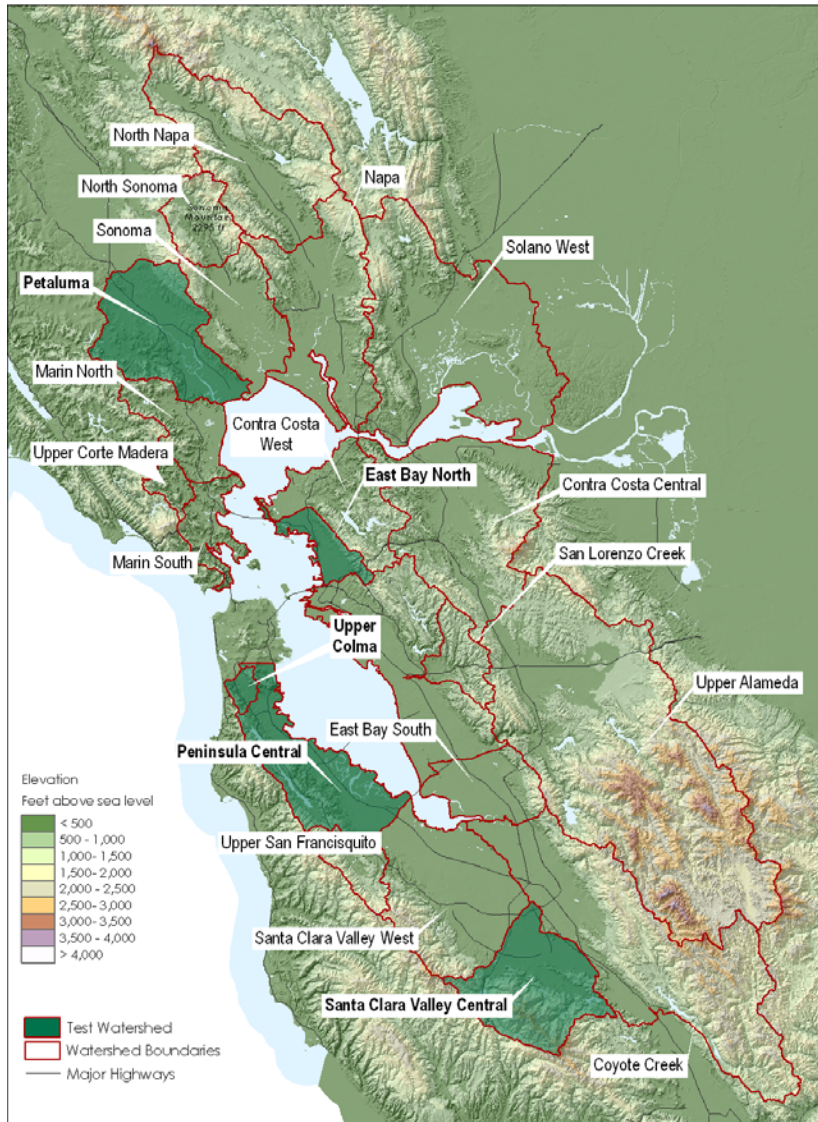
MODELING APPROACH AND PHASE I RESULTS

The watershed modeling package selected for this application is the U.S. EPA's Hydrological Simulation Program-FORTRAN (HSPF) (Bicknell et al., 2005). HSPF is a comprehensive watershed model of hydrology and water quality that includes modeling of both land surface and subsurface hydrologic and water quality processes, linked and closely integrated with corresponding stream and reservoir processes.

Figure 2 shows the 22 sub-watersheds defined for the Phase I San Francisco Bay modeling effort, and the five sub-watersheds (highlighted) that were selected for additional investigation in Phase II. The watershed model represents the local contributions of runoff, sediment, and copper to the Bay;

contributions from the Sacramento/San Joaquin River Delta are not included in the watershed model, but are represented as boundary conditions in the Bay modeling effort (URS, 2006).

Figure 2 - San Francisco Bay Study Area Modeled Sub-Watersheds



For each of the 22 Bay Area sub-watersheds, one stream was identified as the representative reach for that sub-watershed. Furthermore, for many of the sub-watersheds that directly border the Bay, the model includes only a single stream for calculating the Bay inputs even though these inputs are physically distributed among a number of small streams, creeks, and storm drains. Therefore, the model aggregates all the watershed drainage into a single outlet for calculation purposes; the Bay model subsequently distributes these inputs among a number of defined boundary input locations. Ten major reservoirs were identified within the Bay Area sub-watersheds, and their contributing areas were excluded from the modeling under the assumption that little discharge reaches the Bay from these reservoirs.

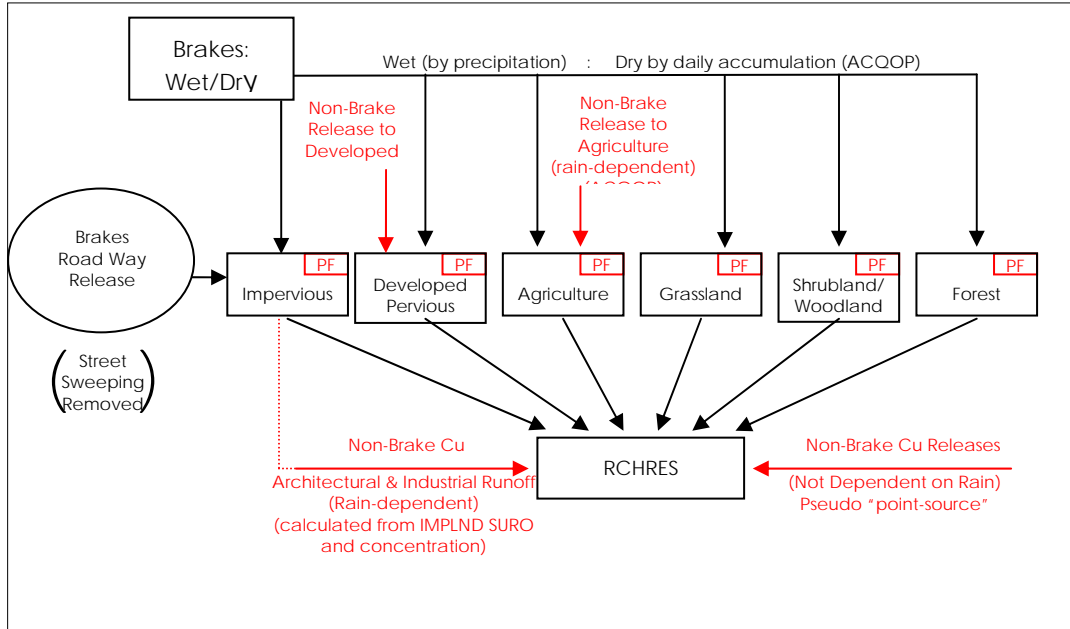
Twenty rainfall stations were selected to represent the precipitation inputs to the 22 subwatersheds. Thiessen analysis was used to assign the appropriate rain stations to each sub-watershed, and adjustment factors were used to adjust the point rainfall for sub-watershed-wide effective rainfall, based on the isohyetal pattern of rainfall over the Bay Area. Since the model requires input potential evapotranspiration to compute the actual evapotranspiration, measured pan evaporation data from San Jose was adjusted to other sub-watersheds using climate zones defined by California Irrigation Management Information System (CIMIS) (CA DWR, 2000).

The sub-watersheds were further subdivided into the various land use categories based on USGS 1992 National Land Cover Dataset (NLCD) data. The NLCD categories were aggregated into five model-simulated categories: agriculture, developed/landscape, forest, grassland, shrub/wooded. The developed/landscape category was represented in the model as both a pervious portion and a directly-connected, impervious area portion.

In semi-arid climates, such as we have in the Bay Area, supplemental irrigation can have a significant impact on the hydrologic regime and stormwater runoff, potentially changing ephemeral streams into perennial ones. Since the developed urban and agricultural land use within the study area comprise about 23% of the total land area, irrigation was applied to these land uses in the model. The crop and lawn irrigation need is calculated as the difference between lawn ET demand and rainfall. For the Bay Area sub-watersheds, the annual supplemental irrigation amounts to 15 to 30 inches, depending on local ET and rainfall contributions.

Figure 3 provides a schematic of how the various copper flux estimates are represented in the watershed model. These include copper from brake pads as wet and dry deposition and brake pad copper deposited directly from vehicles to roadways, i.e., the impervious land category. Copper source inventories (Rosselot, 2006a, 2006b) were performed for the full range of sources shown in Figure 3, sponsored by the BPP. Rain-independent releases to storm drains and surface waters include copper in domestic water discharged to storm drains, copper released from pool, spa, and fountain algaecides, and copper used in algaecides used in non-agricultural rights of way, recreation areas, and for public health. Rain-dependent releases to storm drains and surface waters include architectural releases of copper and copper in industrial runoff. Releases to agricultural land include copper in algaecides applied to agricultural water areas as well as copper in fertilizers and pesticides applied to agricultural land. Releases to developed land include copper in pesticides applied to urban land and copper in non-farm fertilizers as well as copper from pressure-treated wood used in residential and commercial construction. A background level of 25 ppm copper on soils was assumed.

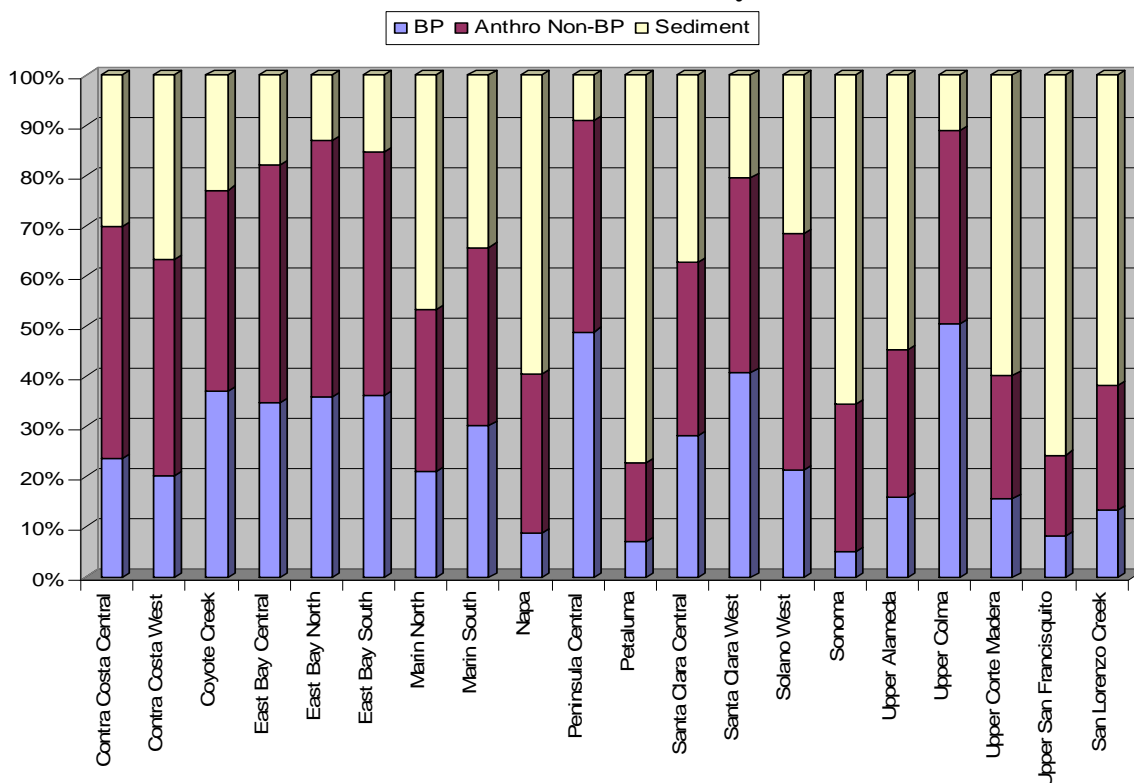
Limited hydrologic calibration was performed in eight of the sub-watersheds where USGS flow data were available, and the resulting model parameters were extended to adjacent/similar watersheds. Similar copper and sediment calibration and consistency checks were performed at three locations.

Figure 3 - Copper Flux Diagram

There is a great deal of uncertainty in both the non-brake and brake release estimates, and taking that uncertainty into account when determining whether the contribution from brake pads is substantial was necessary. Thus, three cases of copper release (flux) scenarios were modeled, one called brakes-high, one called brakes-low, and one called median estimate. One scenario is based on the point value presented in the copper release inventories for both brake sources and non-brake sources; this scenario is called the **median estimate** case. A second scenario, called the **brakes-low** case, explores the source term estimates from the perspective that the point values in the release inventory overestimate brake contributions relative to non-brake sources. The third scenario, called the **brakes-high** case, explores the source terms from the perspective that the point values in the release inventory underestimate brake contributions relative to non-brake sources of copper. These three scenarios were selected because results based on them adequately represent the range of relative contribution of copper released from brakes, and because they take the uncertainty in both brake and non-brake releases into account. Each of these scenarios was modeled with and without releases from brake pads (for a total of six scenarios) in order to determine the relative contribution of copper from brake pads in runoff to the Bay. Model scenario runs spanned the water years 1981-2005. The results are shown in Table 1 and Figure 4. Standard uncertainties for copper release estimates in the Bay Area were presented in Rosselot (2006a, 2006b) and Pun (2007).

Table 1 - Summary of Mean Annual Copper Loads in Runoff to San Francisco Bay for Alternative Scenarios

Scenarios	Total Loads in Runoff*	Non-Brake Pad Contribution*		Brake Pad Contribution	
	kg Cu/yr	kg Cu/yr	% of Total	kg Cu/yr	% of Total
Brakes - High	55,907	36,360	65	19,547	35
Median Estimate	56,465	43,632	77	12,833	23
Brakes - Low	56,769	50,914	90	5,854	10

Figure 4 - Brake Pad, Anthropogenic Non-Brake Pad, and Sediment (Background) Copper Contributions in Runoff to San Francisco Bay

COPPER TRANSPORT AND ACCUMULATION

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 materials are being removed at the same rate they are being deposited (Figure 5). In Phase 1, 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 from the impervious surface and dispersed to adjacent surfaces. In Phase 2, a literature review was conducted and it was determined that copper from roadway surfaces is removed from roadway surfaces to the road buffer and deposits usually within about 10 meters (Sabin *et al.*, 2006; Sutherland and Tolosa, 2001, Hewitt and Rashed, 1991).

The primary methodology for investigating this buildup-washoff formulation 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. The total area was computed as two times the area of all road surface area in the watershed, based on road surface data developed by Dufour and Cooke (2006) for the BPP watersheds. This methodology is illustrated in Figure 6. The equivalent area was removed from the developed pervious area. In a second set of model runs, the buffer areas were assumed to be impervious instead of pervious. This option is assumed to represent a worst-case for the buffer formulation, 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 5 - Copper Losses Due to Buildup-Washoff Approach

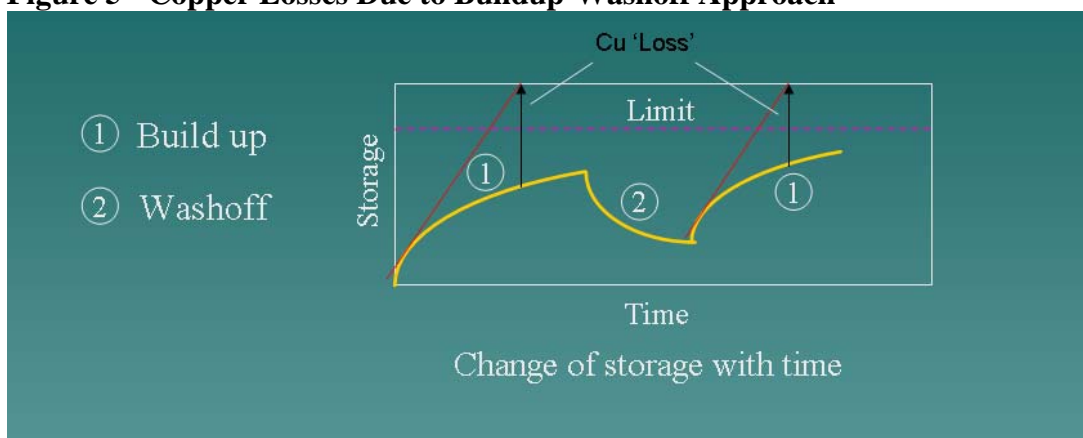


Figure 6 - Conceptual Approach to Roadway Buffers that Receive Copper Losses

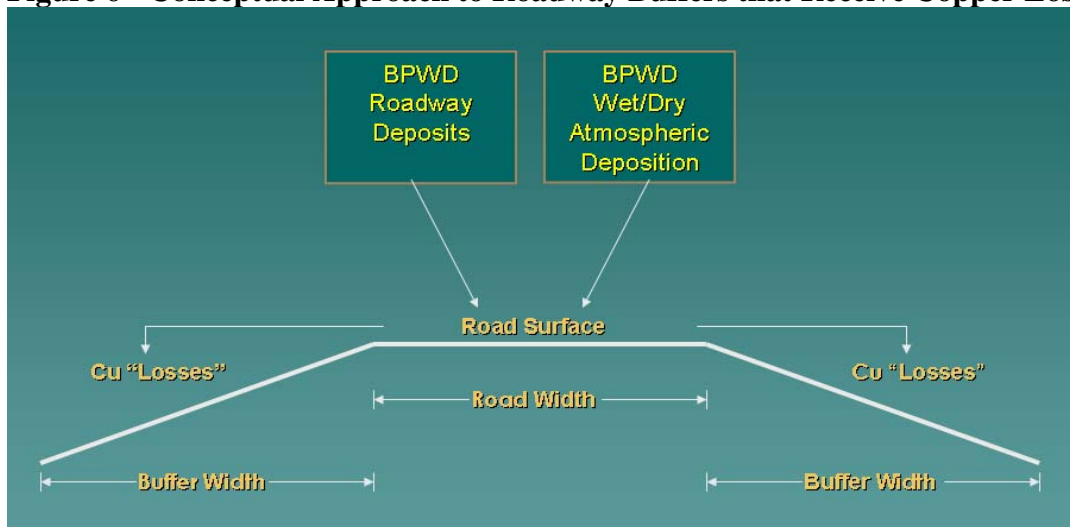


Table 2 - Effects of Roadway Buffers on Copper Loads

	Mid Brakes Load to Bay (kg/yr)	Pervious Buffer		Impervious Buffer	
		Copper Load to Bay (kg/yr)	Percent Change from Mid Brakes	Copper Load to Bay (kg/yr)	Percent Change from Mid Brakes
East Bay North	1,781	1,845	3.6	2,045	15
Peninsula Central	2,682	2,723	1.5	3,452	29
Petaluma	4,742	4,772	0.6	5,689	20
Santa Clara Valley Central	2,645	2,704	2.2	3,478	31
Upper Colma	521	539	3.3	648	24

ANALYSIS OF ACCUMULATION LIMIT AND COPPER EXCHANGE RATES

In addition to the accumulation rate, the other key parameter in the buildup/washoff formulation 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. 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., $1/\text{SQOLIM}$, 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 and the larger values for the other categories.

A sensitivity analysis of SQOLIM was performed for the five test sub-watersheds to determine the effect of varying this parameter for all land uses. The results of this test are shown in Table 3, 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 limit 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; it is not known whether the accumulation limits were set too high, too low, or correctly. Instead, this investigation was done to explore the sensitivity of the model results to uncertainties in the accumulation limits.

The results in Table 3 demonstrate this relationship and show a significant sensitivity, with copper loads changing in the range of 20% to 40% for the urban watersheds, but much less (i.e., 6% - 7%) for the rural Petaluma watershed. Thus the SQOLIM parameter and its corresponding effective loss rate have a significant impact on copper loads.

Table 3 - Effect of Varying Accumulation Limit SQOLIM on Copper Loads

Multiplier of SQOLIM	SQOLIM (Accumulation Limit)									
	x 0.5		x 0.75		x 1.0	x 1.5		x 2.0		
	Copper Load to Bay (kg/yr)	Percent Change from Mid Brakes	Copper Load to Bay (kg/yr)	Percent Change from Mid Brakes	Mid Brakes Load to Bay (kg/yr)	Copper Load to Bay (kg/yr)	Percent Change from Mid Brakes	Copper Load to Bay (kg/yr)	Percent Change 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	

The Phase I modeling identified the stream sediments as the primary 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 test sub-watersheds to determine the effect of varying this parameter. The rates in the Phase I 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 analysis are shown in Table 4.

Table 4 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%	

TIME TO REACH BASELINE COPPER LEVELS AFTER SOURCE HAS BEEN TURNED OFF

A series of model runs was devised to assess the lag time after brake pad wear debris sources have been turned off until copper loads approach the baseline loads (Figure 7). For each sub-watershed and each scenario, three simulation runs were needed to evaluate the time needed to approach baseline conditions, as follows:

Brake Pad Debris-On – This simulation provides loads under conditions of brakepad sources; i.e., essentially the same as the Phase 1 simulation. The initial copper storages were set to the values at the end of the Phase 1 Mid-Brakes 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.

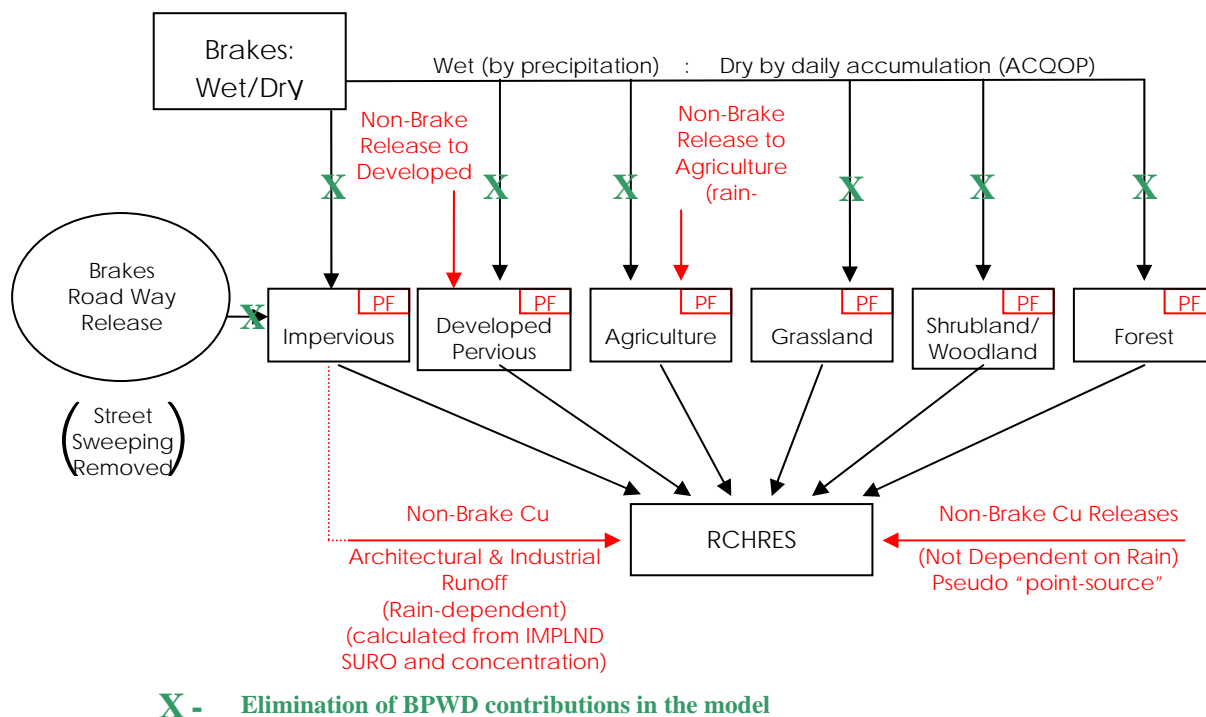
Baseline - This simulation provides loads under conditions of zero brake pad sources. The initial copper storages in this run were set to the values at the end of the Phase 1 - no-brake model run. This represents conditions after a long period of no brake pad sources.

Brake Pad Debris-Off – This simulation provides copper loads for 25 years following the cessation of the brake pad sources at time = 0. The initial copper storages in this run are the same as those in the Brake Debris-On run, i.e., this is assumed to represent conditions after a long period of brake-related sources.

At any time during the simulation, the difference between the annual Brake Pad Debris-On and Baseline loads represents the brake-derived copper under the Brake Pad Debris-On conditions, i.e., the Phase 1 brake contribution in each year. Likewise, the difference between the Brake Pad Debris-Off and Baseline loads represents brake-derived copper under the Brake Pad Debris-Off conditions, i.e., after brake sources have been stopped. The ratio of these two quantities over time provides a measure of the approach to Baseline copper loads, calculated as follows:

$$\frac{(\text{BPWDOff} - \text{Baseline})}{(\text{BPWDon} - \text{Baseline})} = \text{fraction of BPWD - derived Copper that occurred during that year}$$

Figure 7 - Copper Flux Diagram in the Model with BPWD Sources Stopped

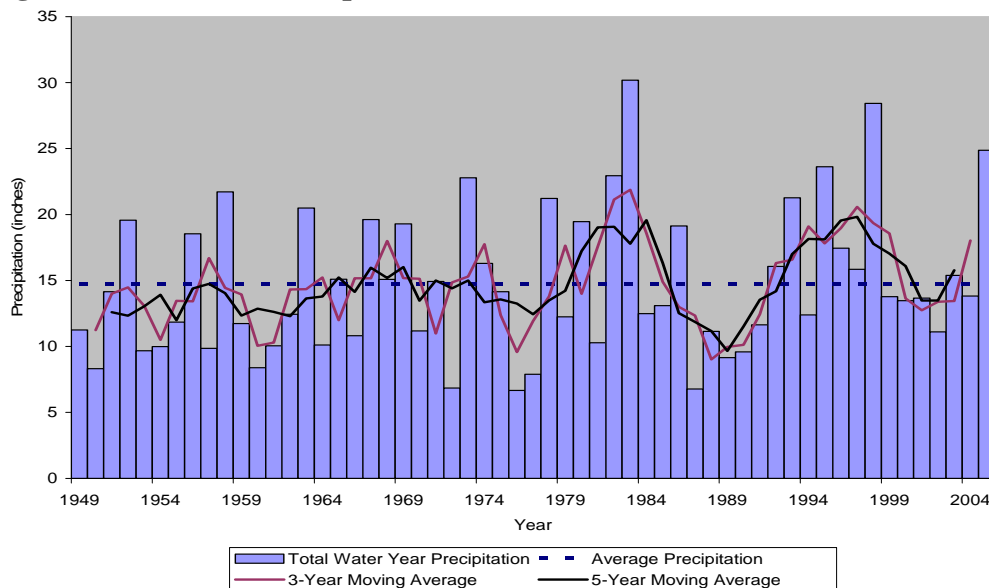


Analyses were performed under both wet and dry meteorological conditions to assess the impacts of climate variability. Figure 8 shows the historical precipitation from about 1950 to

2006, for San Jose. Based on this rainfall record, and others from around the Bay, the following scenarios were run:

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

Figure 8 - Historical Precipitation at San Jose



The results of the 15 scenarios, (the three meteorological scenarios for each of the five test sub-watersheds) were graphed as a function of time, and an example is shown in Figure 9. These plots portray the time it takes for the BPWD-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 results of these runs are summarized by compiling the time it takes to reach 5%, of the original BPWD loads; this percentage also correspond to a 95% reduction in the BPWD loads. Table 5 shows the times required to reach this level based on 5-year increments. To reach a 95% reduction level, two decades or more may be required in some watersheds.

Figure 9 - Reduction in Copper Loads Following Cessation of BPWD Sources in Santa Clara Valley Central (Guadalupe River) Under Historical Meteorological Conditions

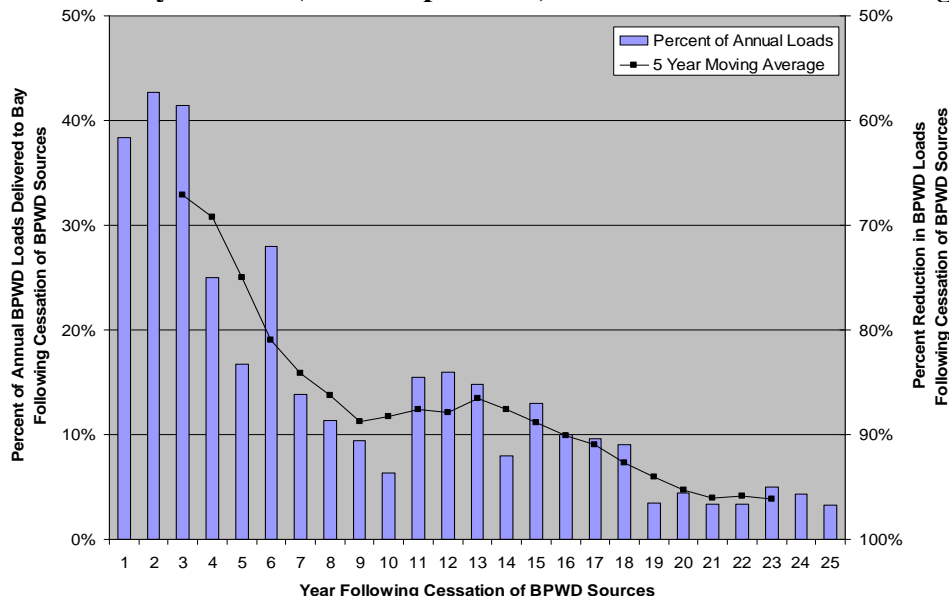


Table 5 - Time Required to Reach 95% Reduction in BPWD Loads

	Time to Reach 5% of Base/Background Cu Loads (years) (95% Reduction in Brake Pad Loads)		
	Historical Met Data, WY84-WY05	Dry Scenario, WY84-WY94	Wet Scenario, WY95-WY05
East Bay North	6 -10	6 -10	0-5
Peninsula Central	6 -10	11 - 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

CLOSURE

The SF Bay Copper Watershed model and scenario analyses has provided critical input to the BPP efforts to assess and ultimately reduce BPWD contributions to the Bay, through both source reduction and regulatory efforts. The model has provided a critical mechanism to more fully understand the components of the BPWD of copper, the relative importance of all sources, and potential time frame over which remediation efforts may ultimately be successful.

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