AWRA 2009 SPRING SPECIALTY CONFERENCE
Anchorage, Alaska
May 4-6, 2009

COPPER RUNOFF TO SAN FRANCISCO BAY FROM BRAKE PAD WEAR DEBRIS: A MODELING ASSESSMENT

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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.

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 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, is to predict through fate 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, 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.

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MODELING APPROACH

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. With local data for land use, soils, topography, and meteorology, the U.S. EPA's HSPF model was set up for each of the 22 Brake Pad Partnership modeled sub-watersheds that drain to the San Francisco Bay (Figure 1). Model parameters and copper sources associated with deposition of copper onto landscape surfaces were obtained from the results of atmospheric deposition modeling conducted for the Brake Pad Partnership by AER, Inc (Pun, 2007) and from release inventory values of brake and non-brake sources from Rosselot (2006a, 2006b). HSPF Model runs were performed for each sub-watershed for the entire time period of water year 1981 through water year 2005. Typical calibration and validation procedures have been well established over the past 25 years as described in numerous reports and journal articles (See Phase 1 Project Report – Donigian and Bicknell, 2007).

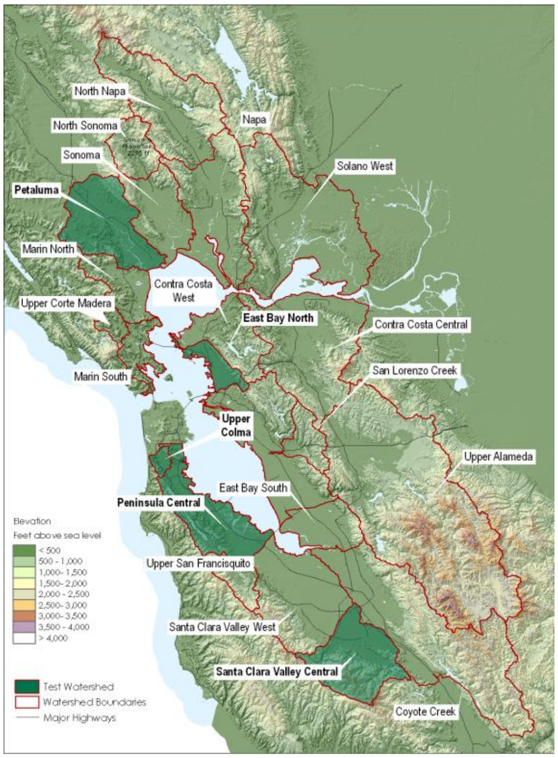

Figure 1. San Francisco Bay Study Area Modeled Sub-Watersheds

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 (Table 1, Figure 2). Standard uncertainties for copper release estimates in the Bay Area were presented in Rosselot (2007a, 2007b) and Pun (2007).

PHASE I RESULTS

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

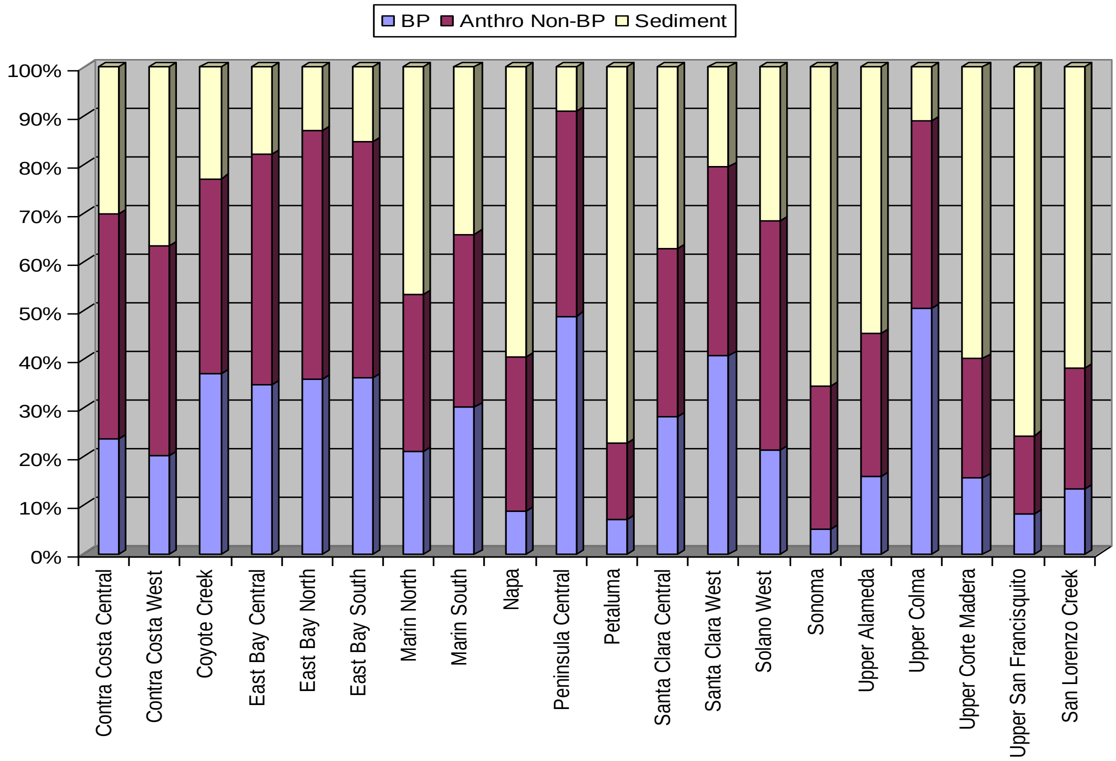

Figure 2. Brake Pad, Anthropogenic Non-Brake Pad, and Sediment (Background) Copper Contributions in Runoff to San Francisco Bay

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 3). 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 to adjacent surfaces (Figure 4). In Phase 2, a literature review was conducted and it was determined that copper from roadway surfaces is moved from roadway surfaces to the road buffer and deposits usually within 10 meters (Sabin *et al*., 2006; Sutherland and Tolosa, 2001, Hewitt and Rashed, 1991). The model formulation was modified to account for this "lost" copper, and model runs were performed for five of the 22 watersheds (Table 2). This was accomplished by moving the copper from the roadway surface to the roadway buffer where it is subject to washoff from surface waters (Phase 2 Report - Donigian *et al*., 2009).

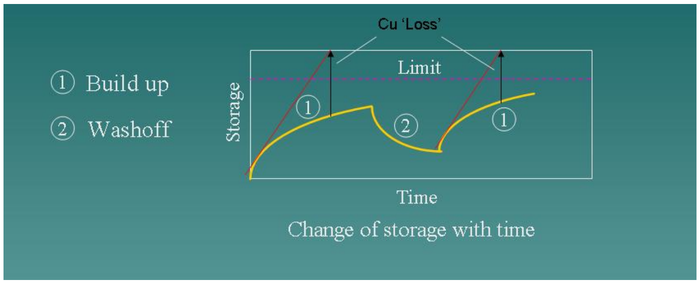

Figure 3. Copper Losses Due to Buildup-Washoff Approach

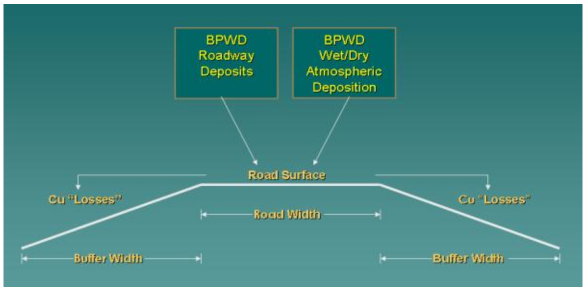

Figure 4. Conceptual Approach to Roadway Buffers that Receive Copper Losses Due to Buildup-Washoff Approach

Table 2 shows the effects of the roadway buffers on copper loading to the Bay on an average annual basis for the five test 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 original report. Accounting for this lost copper also increased the fraction of total copper in releases that is estimated to come from brake sources. These fractions increased (from the Phase 1 results) in the five test watersheds by 2-3% for pervious buffers and 8-17% for impervious buffers.

Table 2. Effects of Roadway Buffers on Copper Loads

	Mid Brakes	Pervious Buffer		Impervious Buffer	
	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	1,781	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 Stream Bed Storage and Copper Exchange Rates

Sensitivity analysis was performed for the accumulation maximum (SQOLIM in HSPF), and other model parameters to evaluate the uncertainty in some 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 (Table 3).

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

	SQOLIM (Accumulation Limit)								
Multiplier of SQOLIM	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

Methodology for Determining Time to Reach Baseline Copper Levels once 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 5). For each sub-watershed and each scenario, three simulation runs were needed to evaluate the time needed to approach baseline conditions, as follows:

BPWD$_{On}$ – This simulation provides loads under conditions of brake pad wear debris (BPWD) sources.

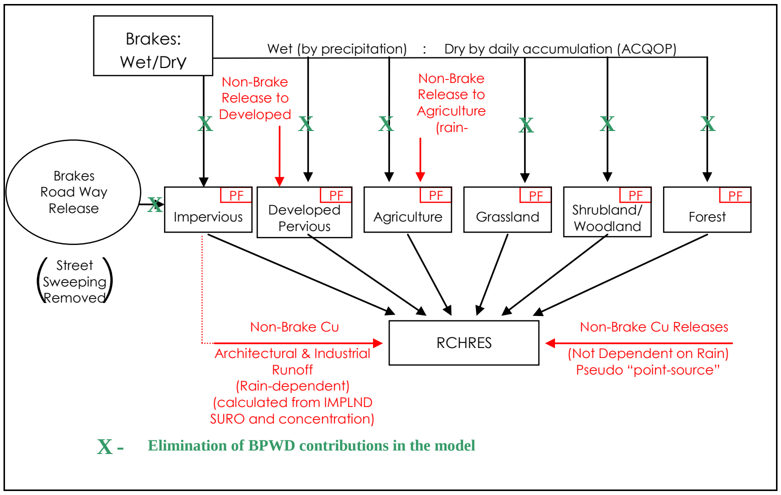

Figure 5. Copper Flux Diagram in the Model with BPWD Sources Stopped

Baseline - This simulation provides loads under conditions of zero BPWD sources.
BPWD$_{\text{Off}}$ – This simulation provides copper loads for 25 years following the cessation of the BPWD sources at time = 0.

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

Meteorological Influences

Analyses were performed under both wet and dry meteorological conditions to assess the impacts of climate variability. Figure 6 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.

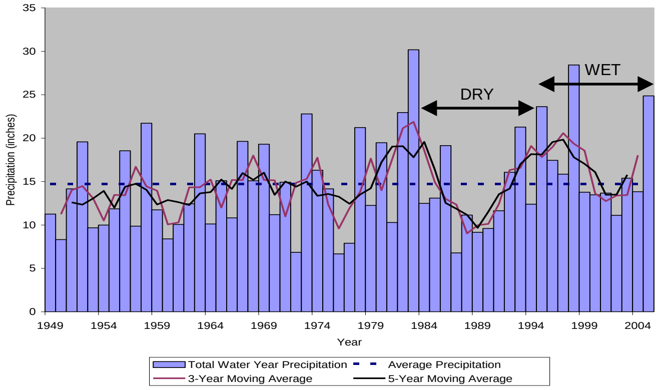

Figure 6. Historical Precipitation at San Jose

PHASE II RESULTS

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 7. 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. Note that the moving averages in these figures are plotted at the mid-points of the 3-year and 5-year time periods.

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 4 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.

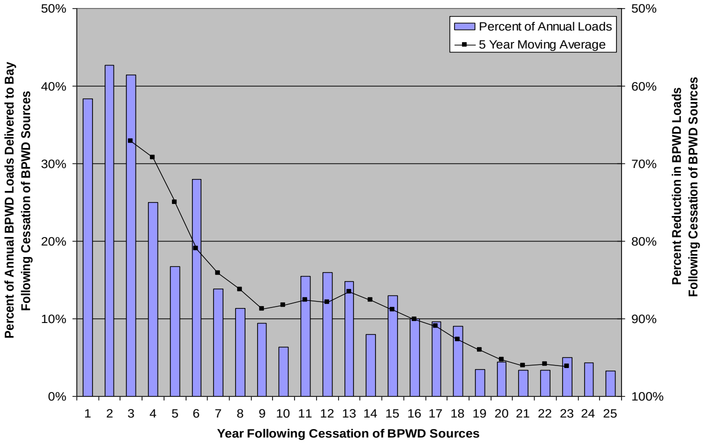

Figure 7. Reduction in Copper Loads Following Cessation of BPWD Sources in Santa Clara Valley Central (Guadalupe River) Under Historical Meteorological Conditions

RECOMMENDATIONS

During this follow-on study, the biggest impacts on copper loading rates from BPWD 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 Mid-Brakes scenario from Phase 1. With increased loadings, time lags are likely to increase. Consequently, we recommend further modeling scenarios be performed to assess the changes in the expected time lags under the following conditions:

Table 4. 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

- Use of Phase 1 High-Brakes scenario loadings in place of the Mid-Brakes values
- Use of Impervious buffers to receive the copper 'loss' due to the model formulations
- Use of higher accumulation limits, if justified by minimal changes to the model calibration
- Reasonable combinations of the above scenarios, as potential worst-case conditions

In addition, during the course of the Phase 1 modeling effort and subsequent peer review, a number of areas and topics were identified where additional investigation was recommended to improve, support, and/or refine the current model estimates of copper loads to San Francisco Bay, and the relative contribution from brake pad wear debris. Most of these recommendations were not addressed in this effort and are briefly listed below; they are discussed in more detail in the Phase 1 report:

- Further calibration and validation with available data, e.g. Guadalupe River in the South Bay Area
- Assessment of Stream Deposition and scour processes and modeling
- Re-consideration of reservoir representation missing from Phase 1 effort
- Increased spatial discretization of SF Bay area sub-watersheds

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