WATERSHED MODELING FOR THE ENVIRONMENTAL FATE AND TRANSPORT OF COPPER FROM VECHICLE BRAKE PAD WEAR DEBRIS

WORK PLAN

Submitted to

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1. INTRODUCTION AND OBJECTIVES

The Brake Pad Partnership (BPP) is coordinating a program of environmental monitoring, environmental modeling, and laboratory studies to understand how brake pad wear debris (BPWD) travels in the environment, and the potential for copper in BPWD to impact water quality. Copper is a component of BPWD that potentially impacts surface water quality in the San Francisco Bay, hence copper is used as an example for this study. This project pertains to storm water mobilization of BPWD and anthropogenically-derived copper deposited on the urban landscape. Storm water represents a potentially important transport link between the deposition of BPWD on roadways and the destination of interest, the San Francisco Bay.

A conceptual model of the atmospheric fate and transport of BPWD was presented by K. Moran (2003). Once released from the wheel well during a braking event, BPWD particles can adhere to the vehicle, become airborne, or deposit immediately onto the road surface. The fraction of BPWD that becomes immediately airborne, together with BPWD initially deposited on streets that is subsequently resuspended into the air, represent “direct” emissions from the viewpoint of air deposition modeling. Airborne BPWD is dispersed by wind. Some portion of material may be carried by atmospheric transport beyond the watershed of concern, and other material may be carried into the watershed from outside. As the BPWD is transported, a fraction of the material deposits on land uses of all kinds including roadways, on buildings, on soils and vegetation, on creeks and rivers, and on the Bay itself. The total BPWD that deposits on impervious surfaces, both immediately and after atmospheric transport, becomes a reservoir for “indirect” emissions to the atmosphere, for example when road dust is entrained into the air by the effects of wind and passing vehicles. This resuspension process may serve to limit the storage of BPWD and copper on impervious surfaces, and increase their storage on pervious surfaces during dry periods.

Two types of deposition processes are of potential importance in atmospheric transport. Dry deposition refers to the removal of particles as they are brought into contact with the ground, vegetation, or structures by atmospheric turbulence or by gravitational settling. Wet deposition of particles typically happens when they are scavenged from the air by falling rain. Deposition via both of these mechanisms onto the Bay itself is one of the pathways for BPWD to enter the Bay. BPWD that deposits onto other areas of the watershed via any of these mechanisms (direct deposition upon braking, wet and dry atmospheric deposition) can also enter the Bay via runoff and subsequent transport in streams. The processes included in this model investigation (emissions, air dispersal, and wet and dry deposition), are shown in Figure 1.

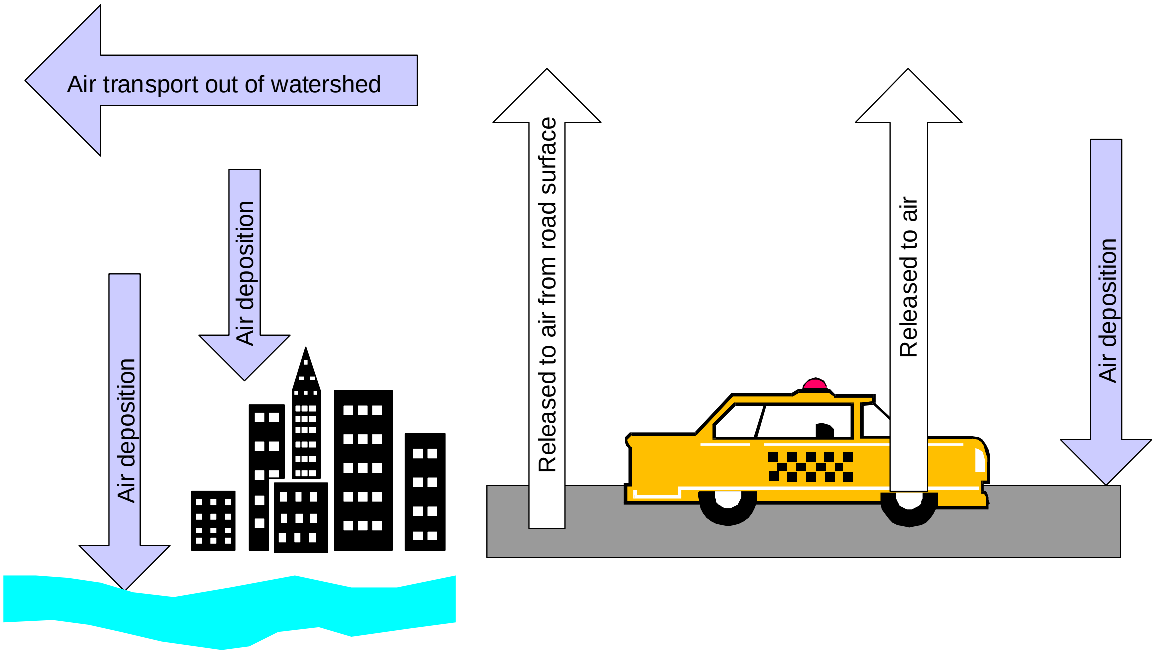

Figure 1. Conceptual model of atmospheric fate and transport of BPWD.

2. MODELING APPROACH

For the modeling described in this report, HSPF (Hydrologic Simulation Program Fortran, version 12) is the primary model that will be used to simulate runoff in the 5.5 square mile Castro Valley watershed (Figure 2), located in Alameda County, California. The model will be calibrated against stream flow and water column monitoring data collected from Castro Valley Creek at the outlet of the watershed. Daily mean flow has been measured by a USGS gauging station at this location since 1971. Water column suspended sediment and total copper concentration data have been collected at the same location intermittently since 1989. Together this information forms a data set that will be used to calibrate the model. Model parameters associated with deposition of copper onto landscape surfaces will be obtained from the results of atmospheric deposition modeling to be conducted for the BPP by AER, Inc.

Water column copper and suspended sediment data were collected by BASMAA from streams draining a number of watersheds in the San Francisco Bay area during the late 1980's through the mid 1990's (Woodward-Clyde, 1996). Analysis of this data suggests that suspended sediments in streams throughout the Bay area are in general substantially enriched in (presumably anthropogenic) copper compared with the presumed average natural soil background of ~25 mg/kg. This analysis also suggests that the degree of copper enrichment in these streams is not related in any obvious way to the percent imperviousness (Figure 2) in the associated watersheds. This in turn suggests that runoff loadings from both pervious and impervious surfaces in the Bay area are important contributors to stream loads of anthropogenic copper.

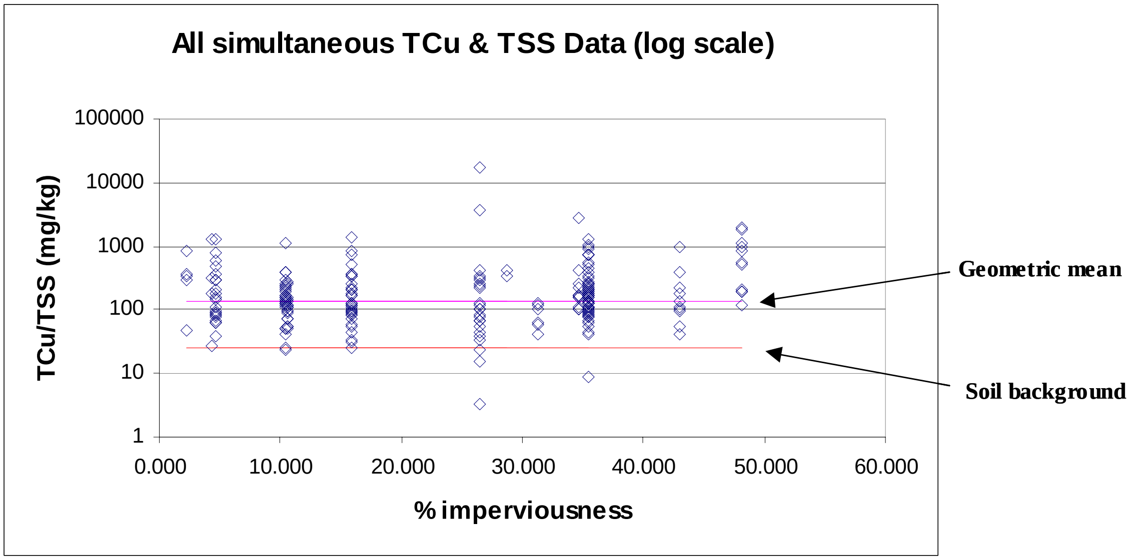

Figure 2. Total copper normalized by total suspended solids in San Francisco Bay area streams as a function of watershed percent imperviousness.

The relative extents to which pervious and impervious land types are responsible for stream copper loads in the Bay area is not known, and can not be quantitatively determined from stream sampling data, even for a well-studied stream like Castro Valley Creek. From a mass-balance perspective it is important to have at least rough estimates of copper loadings from major land uses. For this reason, the use of alternative mechanistic models (*e.g.* SWAT) for generating pervious land runoff load estimates on the basis of the physicochemical properties of copper will be explored. The resulting pervious land runoff load estimates will be used to help inform the selection of pervious land removal and washoff parameters in the calibration of the Castro Valley HSPF model.

With HSPF calibrated against the Castro Valley data, a multi-subwatershed model of all of the land immediately surrounding the Bay (that is, all Bay drainage except for the San Joaquin and Sacramento river drainage areas, which together constitute roughly 40% of the state of California) will be constructed (Figure 3). Model parameters associated with copper build-up will be obtained from the results of regional-scale atmospheric deposition modeling. Parameters associated with copper removal and washoff, including from pervious land uses, will be obtained from the Castro Valley calibration. The scaled-up model will be used to estimate spatially and temporally distributed anthropogenic copper loadings to the San Francisco Bay. The previously mentioned BASMAA data, and other copper monitoring data that can be found from streams draining other watersheds around the Bay, will be used to help verify the HSPF parameter selection and associated Bay copper loading estimates.

The modeling procedure is designed to accomplish both the modeling and sensitivity study objectives in the grant work plan. The type of data needed to provide inputs to watershed runoff modeling is described in Section 2.1. With each input, the associated uncertainties will be compiled to the extent possible.

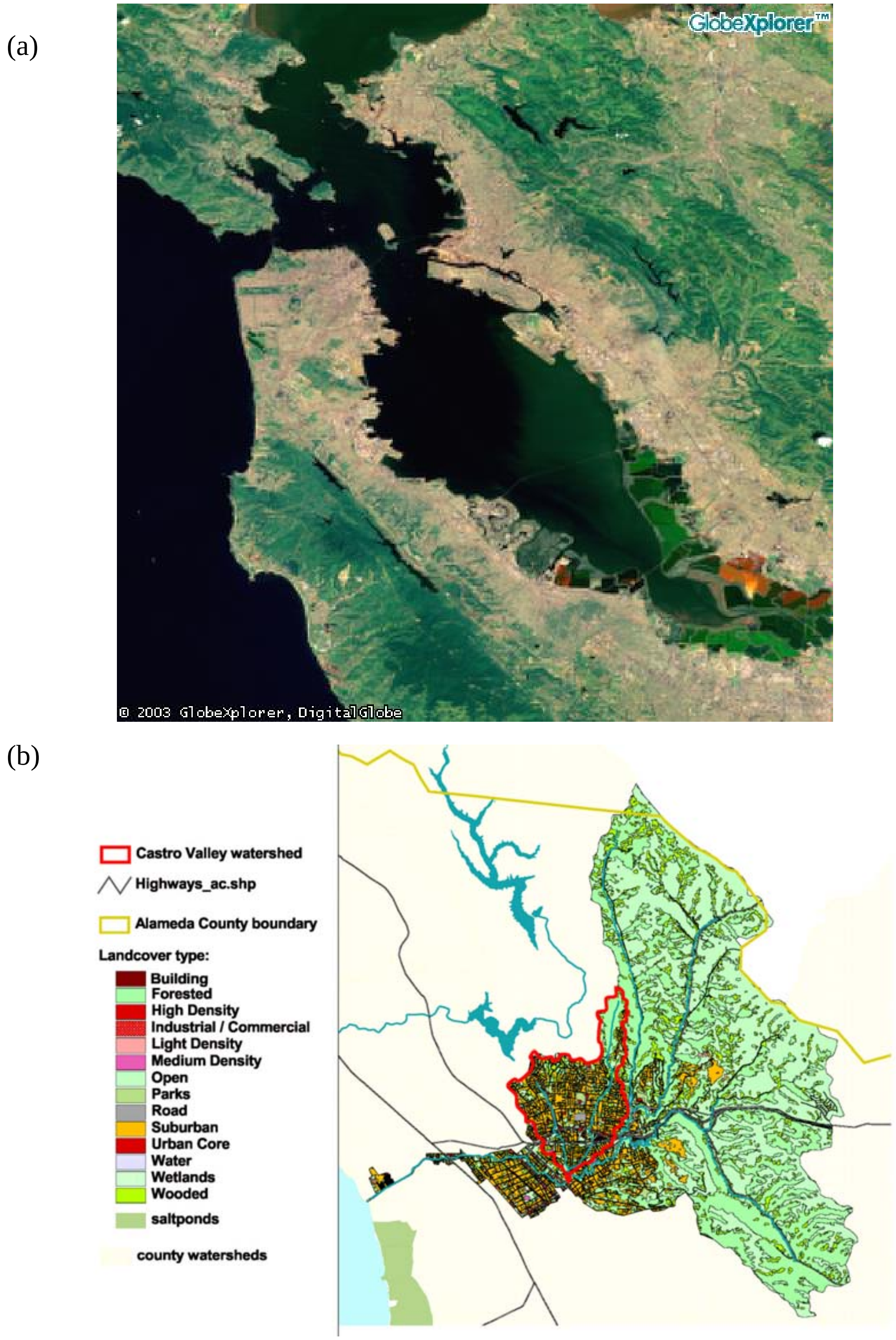

Figure 3. Proposed domains for multiscale modeling: (a) San Francisco Bay Area domain for the box model simulation of regional background (source: http://www.mapquest.com, 2003), (b) the Castro Valley Watershed domain for ISCST simulation of local impacts (source: Pendergast, 2003).

The set up of the Castro Valley model will be discussed in Section 2.2, followed by a discussion of the bay-wide model in Section 2.3. After the model is set up, the calibration of the model to Castro Valley will be conducted (Section 2.4) followed by a sensitivity analysis (Section 2.5). Finally, the Castro Valley calibration will be used to extrapolate the results to the entire Bay for use as an input to the Bay water quality model (Section 2.6).

2.1 Development of Model Inputs

Some of the earliest work to investigate urban pollutant behavior was conducted in Castro Valley in the late 1970s, as part of the National Urban Runoff Program (Pitt and Shawley, 1981). Investigators measured deposition and accumulation of solids (*i.e*. road dirt) and various anthropogenic pollutants including copper on urban streets. Following the cessation of cleansing rain or street cleaning, data showed surface loads initially increasing at a nearly constant rate. As time progressed, the rate of increase tended to decline, with pollutant mass on the surface eventually approaching some upper limiting value in an approximately asymptotic fashion. This plateauing phenomenon was attributed by the authors to the effects of wind and vehicle-induced air turbulence resuspending road solids and contaminants into the air column, from which they presumably settle out somewhere else at a later time. The behavior can be approximated with simple exponential equations such as

$$\frac{dM}{dt} = k_1 - k_2 M \tag{1}$$

which upon integration yields

$$M = \frac{k_1}{k_2}(1 - e^{-k_2 t}) \tag{2}$$

where M is constituent mass (above "permanent storage") on the impervious surface, k_1 is the constituent deposition rate, and k_2 is the rate constant for (non-washoff) constituent removal (Alley and Smith, 1981). Further constituent accumulation becomes zero when surface mass has increased to the point that deposition and removal rates are in equilibrium. Early investigations also showed pollutant washoff from streets to occur in an analogous fashion (Sartor and Boyd, 1972), with the mass remaining on the surface declining as a function of cumulative runoff. This can also be modeled with an exponential equation, for example (Alley, 1981)

$$\frac{dM}{dt} = -k_3 RM \qquad (3)$$

where k_3 (day^{-1}) is the rate constant of removal and R is the runoff rate (*e.g.* cm/hr).

Based upon such findings, exponential build-up and washoff equations were incorporated into SWMM, and subsequently into other watershed models, including HSPF. HSPF is a lumped parameter model, which means that all area classified with a given land use category in a given subbasin is treated as a unit, or 'segment', and represented with a single set of parameters. Segments can be either pervious (PERLND) or impervious (IMPLND), the primary difference being, that infiltration, interflow, and groundwater recharge are modeled only in the former. Storm drainage networks are not explicitly modeled in HSPF. Process equations such as 1 and 3 are used to represent aggregate pollutant behavior within an entire segment, for example for all effective impervious surfaces (streets, sidewalks, roofs, parking lots, etc.) in a watershed considered as a unit.

Equivalent equations in HSPF govern build-up and washoff of pollutants from pervious segments as well. Thus, even with the simplest possible representation of a watershed in HSPF, *i.e*. as consisting of one pervious and one impervious segment, six separate parameters related to anthropogenic copper loadings to streams must be specified. Although the deposition coefficient (k_1) is to be essentially provided for each land segment by the atmospheric deposition modeling results, removal and washoff coefficients (k_2 and k_3) are not known *a priori*, and cannot be estimated based on physicochemical properties. Because the relative load contributions to streams from pervious and impervious areas is not known, parameter indeterminacy results from attempts to calibrate the model simply by matching model predictions against monitoring data, potentially leading to erroneous results in the scaled-up Bay area model of multiple watersheds with varying degrees of imperviousness. For this reason, the use of alternative mechanistic models, in which the process of pervious land pollutant runoff is governed by chemical sorption to soils during overland flow (copper soil sorption coefficients are available in the literature), will be explored in order to derive rough estimates of copper loadings to Castro Valley Creek from the pervious land portion of runoff. Gross loading estimates generated in this fashion will in turn be used to calibrate the “k_2” and “k_3” parameters for the PERLND segment in the Castro Valley HSPF model. The impervious land k_2 and k_3 values can then be estimated by optimization of model predictions against water monitoring data (objective function minimization) from Castro Valley Creek, using automated parameter optimization software (PEST).

2.1.1 Meteorological data

Meteorological data provided with BASINS 3.0 include those from a weather station located at San Francisco airport, which is the only BASINS meteorological station in the San Francisco Bay area. This data set includes hourly precipitation and potential evapotranspiration (PET) for the period between January 1, 1970 and December 31, 1995. To update this information, precipitation and daily minimum and maximum temperature data covering the period between January 1, 1996 and January, 2004 have been purchased by EPA from the National Climatic Data Center (NCDC) (http://www.ncdc.noaa.gov/oa/ncdc.html). Precipitation is a critical forcing function for HSPF and other simulation models. In the San Francisco Bay area, precipitation tends to be highly spatially heterogeneous. To represent spatially heterogeneous precipitation in HSPF simulations of multiple watersheds around the Bay area, data from multiple additional NCDC weather stations will be purchased or otherwise obtained.

2.1.2 Other Data Sources

Other kinds of data used by BASINS in constructing HSPF models include publicly available GIS layers, such as stream and waterbody locations in the National Hydrography Dataset (NHD), land use/land cover in the National Land Cover Dataset (NLCD), land surface elevations in Digital Elevation Model (DEM) data, and the locations of important features such as stream gages and meteorological data stations. Stream gage data (*i.e*. daily mean discharge) for USGS gaging stations, including the one on Castro Valley Creek, is freely available for download from the internet (http://water.usgs.gov/).

2.2 Castro Valley Scale Model Description

The Castro Valley watershed has a mix of urban land uses that are believed to be fairly typical of urbanized areas around the Bay. A USGS gauging station (#11181008) at the outlet of the watershed has recorded mean daily flow continuously since 1971. Alameda County has been sponsoring the collection of water quality data from Castro Valley Creek at the location of the stream gage since the late 1980's. The watershed has been the focus of a number of County-sponsored runoff-related studies as well as previous modeling efforts using SWMM (Khan, 1996). For these reasons the Castro Valley watershed was selected by the BPP to serve as the focus of runoff model calibration.

To model urban watersheds with HSPF, an estimate of the fraction of land covered by directly connected impervious surface is required in order to divide the drainage into PERLND and IMPLND segments. Calculation of percent imperviousness for this exercise is something that can be approached in a number of different ways. For their SWMM modeling, Khan *et al*. (1996) estimated an overall value of 48.3% imperviousness for the Castro Valley watershed, based upon an analysis of aerial photographs of unspecified resolution (Arleen Feng, Alameda County, personal communication). The 2001 version of the National Land Cover Dataset (NLCD) will include coefficients to allow estimates of imperviousness based upon land use coverage in an area, however these data are not yet available for most of the country, including California (http://landcover.usgs.gov/natlandcover_2000.asp). One possible alternative in the meantime is the use of software known as ATtILA (Analytical Tools Interface for Landscape Assessment), under development by the Landscape Ecology Branch of EPA's Office of Research and Development. This software can perform similar calculations upon the 1992 NLCD to estimate percent imperviousness. ATtILA is currently in a beta testing phase and has not been officially released, although release is expected in the very near future (Donald Ebert, personal communication). Using the beta version of ATtILA, imperviousness in the Castro Valley watershed was estimated as 35.5 percent. Another possible source of imperviousness estimates involves an alternative set of 1992 NLCD imperviousness coefficients recently developed by EPA researchers (Jennings *et al.*, in press). Ultimately, various approaches to imperviousness estimation may be tried, and a comparison of results included as part of a sensitivity analysis on model predictions.

2.2.1 Using HSPF Instead of SWMM

Castro Valley Storm Water Management Model (CV-SWMM), developed by the Alameda Countywide Clean Water Program (ACCWP) and its contractor Systech Engineering, Inc. for the Castro Valley was originally proposed for use in the detailed watershed modeling effort. The existing model was to be recalibrated to incorporate new results from other investigations (air deposition, and brake wear debris characterization) in order to estimate the potential contribution of brake wear debris to copper loads discharged from Castro Valley Creek to the Bay. Results from CV-SWMM modeling were to be extrapolated to develop Bay-wide watershed loads using HSPF. Results from HSPF are to be used as input into a hydrodynamic water quality model of the Bay (MIKE 21) to estimate Bay copper concentrations under different loading scenarios.

An alternative to the originally proposed scheme is to use BASINS-HSPF to conduct the detailed modeling of Castro Valley rather than CV-SWMM (one-model approach). This approach has several advantages including:

- HSPF’s pollutant build-up and washoff algorithms are essentially the same as those in SWMM and should provide an equivalent level of predictive capability,
- HSPF has already been initially calibrated to the latest data from Castro Valley Creek.
- Transfer and translation of the SWMM calibration parameters into Bay-wide HSPF is not needed thereby making the extrapolation to other watersheds more straightforward,
- EPA is providing HSPF modeling as in-kind services thereby saving the Project grant money.
- HSPF will have to be calibrated to Castro Valley anyway, before extrapolation to larger watersheds can take place,

The major disadvantage of the one model approach is that the detailed modeling work done in development of CV-SWMM will not be used. CV-SWMM has superior capabilities in modeling urban infrastructure as compared to HSPF. However, due to differences between the set-up and implementation of the two models and the need to extrapolate the SWMM model to HSPF for the extrapolation to the entire Bay watershed, it is unclear how much of the original CV-SWMM calibration parameters would be used in the extrapolation. Developing multiple models for one watershed using one set of data can also provide additional insights into model specific factors that may affect the results.

It should be noted the major work involved in use of either HSPF or CV-SWMM will be to calibrate the hydrology, suspended sediment, and copper against monitoring data, and to integrate the atmospheric deposition modeling results into the calibration. Both models provide similar tools to accomplish these tasks.

2.3 Bay Scale Model Description

Urban areas present some unique challenges in watershed delineation, for example with natural drainage patterns potentially confounded by the storm drain network. Besides a number of major streams, the San Francisco Bay area is drained by perhaps hundreds of additional small streams and storm drains emptying into the Bay. Comprehensive storm drain network maps for the San Francisco Bay drainage area are in the process of being compiled, but do not exist at this time (Eric Wittner, SFEI, personal communication). The City of San Francisco itself is served by a combined sewer system, which delivers some runoff into the ocean rather than the Bay (Arleen Feng, Alameda County, personal communication). The automatic delineation procedure in BASINS, which was used to define the Castro Valley watershed, was found to exclude much of the low-lying urban area when applied to the greater local Bay region. For these reasons it will be necessary to create watershed polygons outside of BASINS, and then import them to create the HSPF project files.

Creating the watershed polygons will involve discussions with the atmospheric deposition and Bay modelers to define a suitable degree of spatial aggregation/resolution. The California Interagency Watershed Mapping Committee’s Calwater 2.0 (http://www.ca.nrcs.usda.gov/features/calwater/) watershed map may serve as an initial template. Boundaries may be added or modified to include watersheds with pour points corresponding to the locations of USGS stream gauging stations.

2.4 Castro Valley Calibration

Preliminary modeling efforts have demonstrated the utility of PEST software (Doherty and Johnston, 2003) for aiding the parameter selection process during calibration of stream flow, as well as water column suspended sediment and total copper in Castro Valley Creek (Carleton and Cocca, 2004). PEST allows the user great flexibility in defining an objective function that quantifies the difference between data and model predictions, and in defining which model parameters are allowed to vary, and in what fashion, in order to minimize the objective function. Using a composite objective function consisting of roughly equal parts weighted-squared differences between measured and modeled daily flows, exceedence times for various flow values, and measured and modeled suspended sediments and total copper, Carleton and Cocca obtained good agreement (*e.g.* r^2=0.87) between measured and modeled daily flow values, and decent agreement between measured and modeled water quality parameters in Castro Valley Creek. For the calibration to be conducted as part of the coordinated BPP modeling effort, PEST will again be used to automate the selection of hydrologic parameters, as well as copper build-up and washoff parameters for impervious surfaces.

2.5 Analysis of Model Sensitivities to Input Uncertainties

To the extent feasible, uncertainty about modeled copper loads to the Bay that derives from uncertainty about the magnitudes of various input parameters will be addressed by propagating potential ranges of parameters through the model in a sensitivity analysis. The adequacy of model predictions will be assessed by comparison of modeled copper loads against measured copper loads, where such information is available from Bay area watersheds other than Castro Valley. This process is expected to be somewhat iterative, and may be used, for example, to adjust copper deposition estimates (k_1) derived from the atmospheric modeling results and the Castro Valley calibration, so as to achieve an optimal match of model predictions with data from multiple watersheds.

2.6 Developing Best Estimates of Deposition

The magnitude of the copper (or BPWD) deposition flux to Castro Valley impervious surfaces is not known, although estimates may be extrapolated from Pitt and Shawley's (1981) data, to provide a rough first approximation. For example, based on Pitt and Shawley's data and certain simplifying assumptions, Carleton and Cocca (2004) estimated 0.0013 lb/acre/day of copper to be deposited to streets in Castro Valley. This value compares favorably with the copper deposition rate (0.0015 lb/acre/day) measured at the shoulder of a major British highway in the late 1980's (Harrison and Johnson, 1985; Hewitt and Rashed, 1991). With information on street width and impervious surface area, this sort of value can easily be scaled up to represent an entire watershed. Atmospheric modeling results and copper deposition monitoring data to be collected as part of BPP activities, along with further calibration against expanded monitoring data sets, should provide improved estimates of deposition rates in the future.

3. REPORT, COORDINATION AND MEETINGS

We anticipate completing the modeling no later than November 15, 2005 so that the draft final report can be prepared by December 20, 2005. This date is contingent upon receiving the final air deposition modeling results by October 14, 2005.

We will participate in meetings with the BPP project team, steering committee and scientific advisory team on a regular basis, either in person or by teleconference. We understand that meetings will be held quarterly or at higher frequencies. We will prepare presentations and provide information to support the BPP Stakeholder Communication Plan.

We will coordinate with the BPP project team to ensure the most effective use of the study results. Several critical areas were identified in the technical approach section:

- Development of percent impervious surface estimates for modeled watersheds,
- Estimation of rates of copper deposition ("k_1") to pervious and impervious surfaces,
- Estimation of resuspension ("k_2") and washoff ("k_3") coefficients for copper on both pervious and impervious surfaces,

- Definition of watersheds (*i.e*. creation of GIS maps) for modeling the greater SF Bay area at a scale that serves the needs of watershed modelers and Bay modelers,
- Development of a scientifically-defensible strategy for "scaling-up" the Castro Valley watershed calibration results.

We will provide brief written monthly progress reports to BPP and stakeholders via e-mail and brief quarterly verbal updates to the steering committee. The final version of the report will be submitted within one month of receiving the final summary comments from stakeholders. The report deliverable will be provided in Acrobat and Microsoft Word formats.

Close communication between modelers is very important, especially given the short time between the air deposition modeling due date and the draft watershed modeling report due date. We will need to be provided with preliminary air deposition simulation results as early as possible (*i.e*. well before receipt of the final air modeling report) in order to conduct preliminary model set-up and calibration, so that final watershed modeling can proceed on schedule to meet the specified due dates.

4. SCHEDULE

Table 1. Project time line.

Task	**Date**
Preliminary calibration of Castro Valley HSPF model, upon final receipt of monitoring data	06/30/2005
Preliminary "scaled-up" modeling of local Bay area runoff	09/15/2005
Final calibration of Castro Valley HSPF model, after receipt of final air deposition modeling report, due 10/14/2005	10/30/2005
Final "scaled-up" modeling of local Bay area runoff	12/01/2005
Draft modeling report finalized	12/20/2005

5. BUDGET

All work under this task is provided by U.S. Environmental Protection Agency as an in-kind no-cost contribution to the project.

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