

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

DRAFT WORK PLAN

Submitted to

Sustainable Conservation
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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 airborne represents “direct” emissions from the viewpoint of air deposition modeling. Airborne BPWD is dispersed by wind. Some portion of material may be carried beyond the watershed of concern. As the BPWD is transported, a fraction of the material will deposit within the watershed on 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 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.

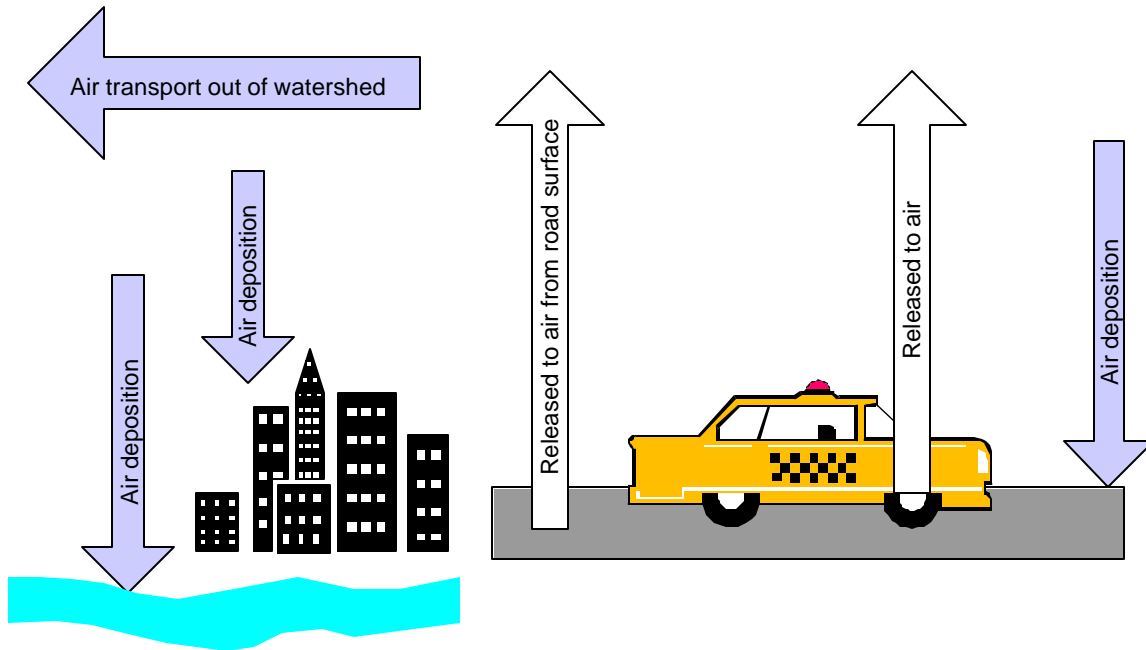


Figure 1. Conceptual model of atmospheric fate and transport of BPWD.

2. MODELING APPROACH

For the modeling described in this report, HSPF 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 build-up and wash-off of copper from impervious surfaces will be obtained in part from copper deposition monitoring data to be collected by the BPP, in part from the results of

atmospheric deposition modeling, and in part by optimization of HSPF parameters so that model simulations most closely match the available water column data.

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 2). Model parameters associated with copper build-up and washoff will be obtained in part from the results of regional-scale atmospheric deposition modeling, and in part from the Castro Valley calibration. The model will be used to estimate spatially and temporally distributed anthropogenic copper loadings to the San Francisco Bay. Water column copper monitoring data, where available from streams draining other watersheds around the Bay, will be used to help verify the reasonableness of model 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.

(a)



(b)

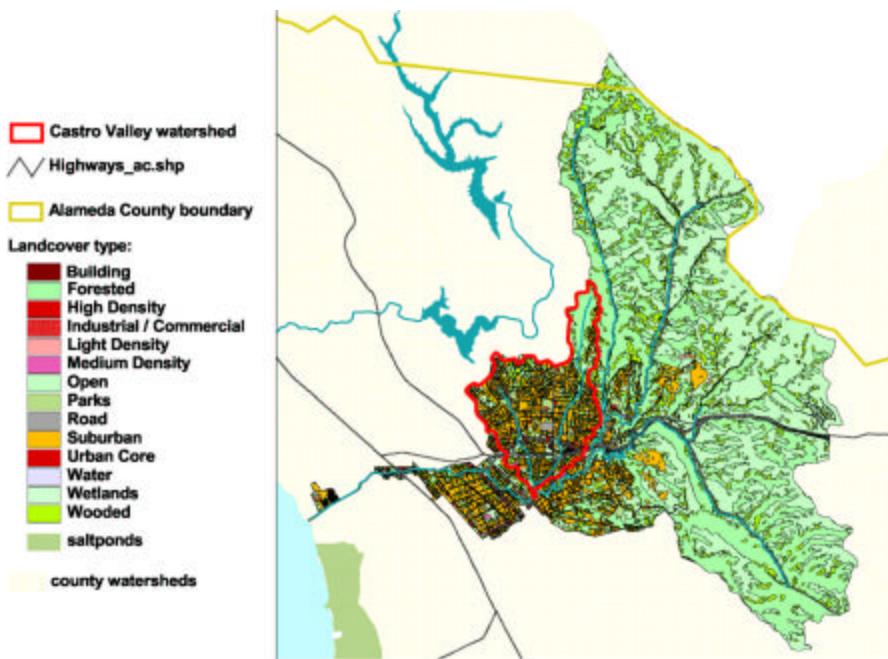


Figure 2. Proposed domains for multiscale modeling: (a) San Francisco Bay Area domain for the box model simulation of regional background (source: <http://www.mapquest.com>, 2003), (b) the Castro Valley Watershed domain for ISCST simulation of local impacts (source: Pendergast, 2003).

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

$$\frac{dM}{dt} = k_1 - k_2M \quad (1)$$

which upon integration yields

$$M = \frac{k_1}{k_2}(1 - e^{-k_2t}) \quad (2)$$

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)

$$\frac{dM}{dt} = -k_3 R t \quad (3)$$

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. Values of k_1 , k_2 , or k_3 determined at one or a few specific points do not necessarily provide useful inputs for a model like HSPF, unless they can be extrapolated to represent average processes within a segment. Parameters that cannot be estimated in this fashion may be best determined by iteratively adjusting them to match model predictions against concentrations measured at the watershed outlet.

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 (<http://www.ncdc.noaa.gov/oa/ncdc.html>). To represent spatially heterogeneous precipitation in modeling, area-weighted average mean annual precipitation will be found

by intersecting watershed boundaries with a map of isohyetal contours (<http://gis.ca.gov/catalog/BrowseRecord.epl?id=5327>) for the Bay area. Ratios between mean annual watershed precipitation and precipitation at SF airport will be used as multipliers on the hourly precipitation at the airport for individual modeled watersheds.

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 Flood Control and Water Conservation District and Alameda Countywide Clean Water Program (ACCWP) have 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 ACCWP-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 Public Works Agency, 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, which 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, several 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 is already 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 Public Works Agency, 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. Bay modelers have not yet indicated to us the degree of spatial resolution they need from the watershed model results in order to provide useful inputs for their models.

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 impervious surfaces,
- Estimation of resuspension (“ k_2 ”) and washoff (“ k_3 ”) coefficients for copper on 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, especially for watersheds and areas without water quality monitoring data.

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.

6. REFERENCES

- Alley, W.M., 1981. Estimation of Impervious-Area Washoff Parameters. *Water Resources Research* 17(4):1161-1166.
- Carleton, J.N. and P. Cocca, 2004. Using HSPF to model pollutant runoff in an urban watershed. In Proceedings: Geographic Information Systems and Water Resources III, AWRA Spring Specialty Conference, May 17-19, Nashville, TN.
- Harrison, R.M. and W.R. Johnston, 1985. Deposition Fluxes of Lead, Cadmium, Copper and Polynuclear Aromatic Hydrocarbons (PAH) on the Verges of a Major Highway. *Science of the Total Environment* 46: 121-135.
- Hewitt, C.N. and M.B. Rashed, 1991. The Deposition of Selected Pollutants Adjacent to a Major Rural Highway. *Atmospheric Environment* 25A(5/6):979-983.
- Jennings, D.B., S.T. Jarnagin, and D.W. Ebert. A modeling approach for estimating watershed impervious surface area from National Land Cover Data 92. *Photogrammetric Engineering and Remote Sensing* In press.
- Khan, O.U., G.W. Shawley, C.L. Chen, C.W. Chen, 1996. Castro Valley Water Quality Modeling: Calibration and Verification, prepared by Systech Engineering Inc. and the Alameda County Flood Control & Water Conservation District, July.
- Pitt, R. and G. Shawley, 1981. San Francisco Bay Area National Urban Runoff Project – A Demonstration of Nonpoint Source Pollution Management on Castro Valley Creek. Prepared for the Environmental Protection Agency in cooperation with Woodward-Clyde Consultants, June.
- Sartor, J.D. and G.B. Boyd, 1972. Water Pollution Aspects of Surface Contaminants. U.S. Environmental Protection Agency, EPA-R2-72-081.