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THE SAN FRANCISCO BAY WATERSHED MODEL FOR COPPER RUNOFF FROM BRAKE PAD WEAR DEBRIS: Part I – GIS Data Processing for Model Setup

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ABSTRACT: This watershed modeling effort was conducted as part of a larger study by the Brake Pad Partnership (BPP), a multi-stakeholder effort of manufacturers, regulators, stormwater management agencies and environmentalists working together to better understand the impacts of copper from brake pad debris on water quality in the San Francisco Bay Region. The watershed model provides runoff loads to a Bay modeling effort to assess resulting concentrations in SF Bay, with the objective of assessing how the contribution of copper from brake pads affects both the short-term and long-term concentrations of copper in the Bay. This paper describes the model set up process and GIS processing of relevant data layers to efficiently produce watershed modeling inputs for the U.S. EPA BASINS system that was used for the watershed modeling component of this effort; a companion paper describes the model application process and loading results produced by the effort as input to the Bay modeling component. Local and national-scale data for land use, soils, topography, hydrography, and meteorology were processed within the BASINS framework to generate model input files for the U.S. EPA's Hydrological Simulation Program-FORTRAN (HSPF) model for each of the Brake Pad Partnership modeled sub-watersheds that drain to the San Francisco Bay. Selected model parameters were estimated through overlays of soils, topography, and land use GIS layers onto the watershed delineations to establish parameter values within each of the sub-watersheds.
KEY TERMS: BASINS, HSPF, Watershed Analysis, Watershed Modeling, Open-Source GIS

INTRODUCTION

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 released to the environment in the San Francisco Bay Region. The BPP is multi-stakeholder effort of manufacturers, regulators, stormwater management agencies and environmentalists working together to better understand the impacts of this source of copper on water quality. The watershed model provides runoff loads to a Bay modeling effort to assess resulting concentrations in San Francisco Bay. The BPP also has sponsored studies of source releases, water quality monitoring, and air deposition monitoring studies specifically to provide input data for these watershed and Bay modeling efforts. Other Brake Pad Partnership studies, such as air deposition monitoring, procurement of a representative sample of brake pad wear debris, and physical and chemical characterization of brake pad wear debris, indirectly provided information that supported these efforts.

The U.S. EPA Office of Science and Technology (OST), working with the Brake Pad Partnership, developed a watershed modeling work plan that was subsequently reviewed and revised as a result of peer review comments. AQUA TERRA Consultants was contracted to perform the modeling as specified in the approved work plan (Carleton, 2004) with selected refinements that were subsequently approved by the BPP Steering Committee. The objective of the environmental transport and fate modeling components was to predict 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. Complete details and results of the watershed modeling effort are presented in Donigian and Bicknell (2007), and for the Bay modeling effort in URS (2007).

Local and national-scale data for land use, soils, topography, hydrography, and meteorology were processed within the U.S. EPA BASINS (EPA, 2007) system framework to generate model input files for the U.S. EPA's Hydrological Simulation Program-FORTRAN (HSPF) (Bicknell, 2005) model for each of the 22 Brake Pad Partnership modeled sub-watersheds that drain to the San Francisco Bay. Selected model parameters were estimated through overlays of soils, topography, and land use

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layers onto the watershed delineations to establish parameter values within each of the sub-watersheds. Due to the large scale of this modeling effort coupled with a relatively modest budget, efficiency in the model setup process was essential to deliver a product that could be used to produce loading results to feed the Bay modeling component in the later stages of the larger study. The BASINS open-source GIS platform provided an avenue to develop extendible tools for mass production and modification of HSPF input files.

GIS DATA LAYERS

Watershed modeling with HSPF requires both spatial data to characterize the land area and time series data for precipitation and evaporation to drive the model functions and quantify the variability in meteorologic conditions across the study area. The spatial data is used to both determine the sub-watershed boundaries and then to characterize the land use, soils, slopes, and hydrography within each of the separate sub-watersheds that drain to the San Francisco Bay. Significant meteorologic data are needed to model in an area such as the San Francisco Bay Area where micro-climates provide great spatial variability in meteorologic conditions. The meteorologic data for this model include only precipitation and evaporation; although snow occasionally occurs on some of the mountain tops of the Bay Area, such as Mount Diablo, Mount Hamilton and Mount Tamalpais, it rarely remains long enough to have a significant impact on local hydrology, and can usually be eliminated from the required model processes.

The sub-watershed boundaries were determined by EPA and approved by the Brake Pad Partnership Steering Committee prior to initiation of the watershed modeling effort. The watersheds shown in Figure 1 are referred to as the 'Brake Pad Partnership modeled watersheds' or 'sub-watersheds' to distinguish them from other local watersheds with similar names but different boundaries. The sub-watershed boundaries were used directly as described in the Watershed Modeling Work Plan (Carleton, 2004), with a few minor modifications. A number of the sub-watersheds shown in Figure 1 deviate from their 'true' hydrologic boundaries in that they are physically separated from the Bay, i.e. their hydraulic connection to the Bay is not included as part of the sub-watershed's area. For example, this occurs for Upper Corte Madera, Upper Colma, Upper San Francisquito, Santa Clara Valley Central, and San Lorenzo Creek. For each of these cases we have included in the model a stream reach, downstream of the 'sub-watershed outlet' so that the location of the true outlet to the Bay is defined for the Bay Model. In addition, selected large subbasins with major reservoirs were subdivided to allow extraction of non-contributing areas above the reservoirs.

The boundaries mostly follow hydrologic divides and are entirely appropriate for the scale of the modeling effort. Note that for many of the sub-watersheds that directly border the Bay, the model setup 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. Thus the model setup, by necessity, aggregates all the watershed drainage into a single outlet for calculational purposes; the Bay model subsequently distributes these inputs among a number of defined boundary input locations. 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 include in the watershed model, but are represented as boundary conditions in the Bay modeling effort (URS, 2007).

Stream segments for the model were derived from the National Hydrography Dataset (NHD) in BASINS (http://www.epa.gov/waterscience/basins/b3webdwn.htm). For each of the 22 Bay Area sub-watersheds, one stream was identified as the representative reach for that sub-watershed. In many cases the 'Level' attribute from the NHD provided an indication of the most appropriate choice of representative reach within each sub-watershed, as this attribute indicates stream order. Within some sub-watersheds multiple streams had been assigned the same 'Level' value in NHD, and so the stream with the greatest length was chosen to be the representative reach in those cases.

Ten major reservoirs, with drainage areas in the range of 20 square miles or greater, were identified within the Bay Area sub-watersheds, and their contributing areas were subsequently excluded from the modeling. This approach is reasonable and consistent with other local studies on runoff contributions to the Bay by Davis et al (2000) and Olivia Chen Consultants, Inc. (2000). In addition, exclusion of the contributing area of these reservoirs was a needed assumption in the modeling effort due to limited time, resources, and data needed to fully investigate and model their operations. Contributing area to these reservoirs was delineated through GIS using the 'Catchments' layer from the NHDPlus dataset (http://www.horizon-systems.com/nhdplus/). The NHDPlus dataset is the latest version of NHD, developed as a joint effort between the USEPA and the USGS, containing more data and attributes than the NHD in BASINS. The NHDPlus 'Catchments' also were used to subdivide several of the largest of the Bay Area sub-watersheds, including Solano West, Coyote Creek, and Upper Alameda into sub-watersheds at a size more consistent with the rest of the sub-watersheds of the study area. A representative reach was chosen from within each of these subdivided sub-watersheds.

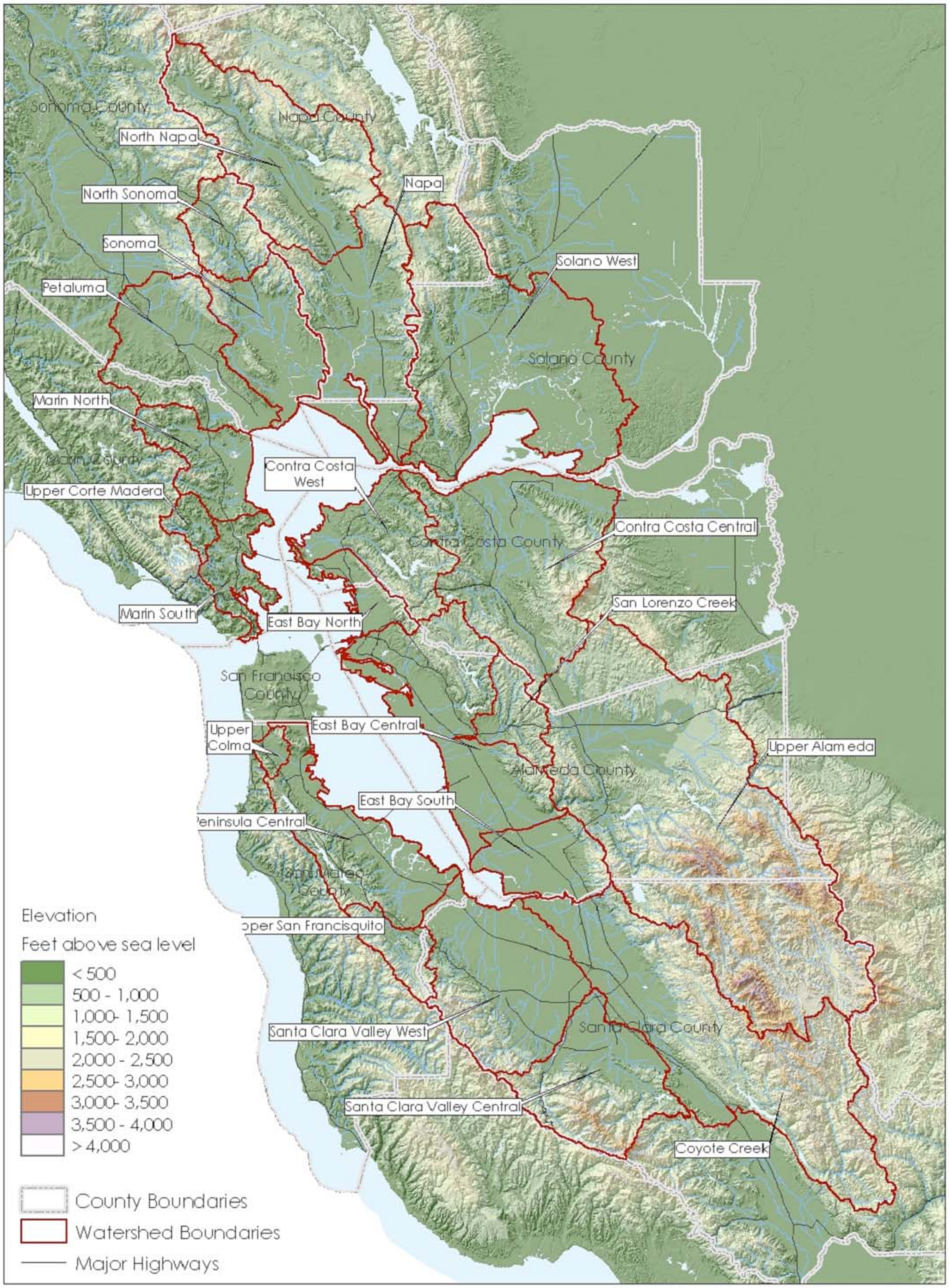

Figure 1: San Francisco Bay Study Area and Brake Pad Partnership Modeled Sub-Watersheds

Once the GIS layers of stream segments and sub-watersheds were developed, the BASINS 4.0 manual delineation tool was used in conjunction with the National Elevation Dataset (NED) in BASINS to calculate stream attributes including length, endpoint elevations, slope, and contributing area for each modeled stream segment. The stream length and slope values were computed for application to the corresponding HSPF hydraulic parameters. Also through the BASINS manual delineation tool the mean depth and mean width of each stream segment was calculated as a function of upstream area. A volume-stage-discharge function (FTABLE) was computed for each stream segment using these values through the algorithm in the interface to HSPF through BASINS, WinHSPF.

Land use affects the hydrologic response of a watershed by influencing infiltration, surface runoff, and water losses from evaporation or transpiration by vegetation. The movement of water through the system, and subsequent erosion and chemical transport, are all affected significantly by the vegetation, (*i.e*., crops, pasture, or open), soils, slopes and associated characteristics (e.g. surface roughness). In addition the land use also helps to better represent the non-brake pad copper source fluxes that are often a function of land use categories and associated activities, e.g. urban/developed versus agriculture. The USGS 1992 National Land Cover Dataset (NLCD) land use coverage (http://landcover.usgs.gov) was selected by the Brake Pad Partnership Steering Committee as the land use data for this effort (Connick and Liao, 2006). The NLCD categories were aggregated into five model-simulated categories – agriculture, developed/landscape, forest, grassland, shrub/wooded – and were overlaid onto the sub-watershed boundaries to determine the land use amounts within each modeled watershed. Due to the importance of impervious surfaces in an urban environment in contributing both stormwater volumes and contaminants, the 'developed/landscape' category was represented in the model as both a pervious portion and a 'directly connected impervious area' (DCIA) portion.

For soils information, SSURGO soils data was obtained from the USDA Soil Data Mart (http://soildatamart.nrcs.usda.gov/) for the Bay Area counties, and processed to identify soil textural classifications and correlate those classes with the SCS hydrologic soil groups (HSG). Thus, sand and sandy loam type soils were assigned to the HSG A, silt and silty loam soils were assigned to HSG B, etc. until all soil units were assigned to one of the four HSG. The only area of missing data was for Western Santa Clara County whose soil survey was ongoing and would not be completed for another few years. Fortunately a comparable HSG map was obtained for that region. The primary HSG for each of the 22 sub-watersheds was determined through GIS processing of this data layer and provided the basis for assigning model parameters to each sub-watershed and each model land use category.

For slope information, a 30-meter digital elevation model (DEM) was obtained for the Bay Area counties from the USGS Seamless data web site (http://seamless.usgs.gov/). The data were processed to calculate mean slopes by land use within each of the 22 sub-watersheds; these data are directly input to the model as a physical attribute of the land surface for each land use category.

Required meteorologic inputs for HSPF for the San Francisco Bay sub-watersheds include precipitation and evaporation. Precipitation is required as short time interval values, usually on an hourly time step, whereas evaporation can be input as daily values that are then distributed over daylight hours using standard procedures available within BASINS. For the precipitation data, this project benefited from the coincident ongoing effort to update the BASINS national database of 500 stations, for the previous version circa 1995, to almost 6000 daily stations and 3600 hourly stations nationwide.

20 stations were selected to represent the precipitation inputs to the 22 sub-watersheds in the Bay Area. These stations were selected from a review of the available hourly and daily stations within the Bay area and local isohyetal patterns; data for selected daily stations were disaggregated using the distribution at neighboring or closest hourly stations with similar daily rainfall totals. These procedures produced a complete set of stations with hourly values for all 22 sub-watersheds within the Bay Area. A Thiessen analysis, a standard hydrologic technique to define the watershed area that will receive the rainfall recorded at the gage, was used to assign the appropriate rain gages to each sub-watershed, and then to develop an adjustment factor to adjust the point rainfall for sub-watershed-wide effective rainfall, based on the isohyetal pattern available in published isohyetal maps.

For evaporation, HSPF generally uses measured pan evaporation to derive an estimate of lake evaporation, which is considered equal to the potential evapotranspiration (PET) required by the model, i.e., PET = (pan evap) X (pan coefficient.) The actual simulated evapotranspiration is computed by the program based on the model algorithms that calculate dynamic soil moisture conditions, as a function of the rainfall, model ET (evapotranspiration) parameters, and the input PET data. For this project pan evaporation data are only available from the Los Alamitos gage in San Jose. In order to adapt this evaporation data to other parts of the study watersheds, climate zones defined by California Irrigation Management Information System (CIMIS) (http://wwwcimis.water.ca.gov/cimis/data.jsp) as shown in their WUCOLS (Water Use Classifications of Landscape Species) manual (CA DWR, 2000) were used. Using these CIMIS zones, the Los Alamitos evaporation data was adjusted to other sub-watersheds by the ratio of the CIMIS values for the corresponding zones.

EXPEDITED MODEL SETUP

The modeling study area for this project is approximately 3500 square miles, comprising almost all of four entire USGS 8-digit hydrologic cataloging units. Constrained by resources typical of a modeling study of a much smaller scale, an expedited approach was needed to extract the available data from the GIS layers and develop model inputs. This large-scale setup was possible because of a sound foundation of prior modeling efforts within the Bay Area, and through customization capabilities made possible during recent and ongoing development efforts of the EPA BASINS system.

Several previous studies provided the technical basis for the HSPF model development and initial parameterization for the study watersheds. One of the primary sources was the HSPF parameter development for the Bay Area Hydrology Model (BAHM) design tool (Clear Creek Solutions, 2007) through calibration studies in Castro Valley and Upper Alameda Creeks (AQUA TERRA Consultants, 2006). Other previous studies included the use of HSPF for multipurpose design of detention facilities in Calabazas Creek of San Jose for the Santa Clara Valley Water District (Donigian, et al., 1997), which included copper runoff modeling, and the application of HSPF to Castro Valley Creek by U.S. EPA for copper runoff modeling (Carleton and Cocca, 2004). These studies provided the knowledge base to estimate hydrology model parameters as extensions from the HSPF models of these calibrated watersheds to all 22 sub-watersheds, and the modeling efforts in Calabazas Creek and Castro Valley Creek provided comparable information for the sediment and copper modeling parameterization. HSPF hydrology parameter values for combinations of land cover/vegetation, soils groups (HSG), and slopes were assigned to the 22 sub-watersheds by land use category as the initial model parameterization based on the soils and slopes characterization of each sub-watershed.

Recent developments with the BASINS software development path provided means to apply parameters quickly and efficiently to the 22 model sub-watersheds. BASINS is now based upon an open-source GIS platform that makes the entire code base of the system available, and BASINS has a scripting capability that allows software components to be used by scripts written in standard programming languages.

The latest release of BASINS, Version 4.0, is based upon an open source GIS package known as MapWindow (http://www.MapWindow.org). A major benefit of being built upon an open source foundation is that the BASINS system can now be available to any user without cost. No prerequisite commercial software is required (other than the Windows operating system), so there are no financial hurdles to impede use of the BASINS system by anyone who wants to use it. But perhaps more importantly, the move away from proprietary GIS means that all source code upon which BASINS is dependent is open and freely available to the federal government and all end users.

MapWindow provides BASINS with a fully functional GIS foundation, including a complete GIS application programming interface (API) for both vector (shapefile) and raster (grid) data. MapWindow is a component based GIS platform that includes a core standalone library of GIS functions and an end-user graphical user interface with a plug-in architecture. As an open source end user GIS tool, MapWindow builds upon and takes advantage of several widely used GIS data and geoprocessing libraries, allowing it support both raster and vector data manipulation in most common file formats. Because of its open source distribution, a worldwide development community is contributing to the already wide feature set contained in MapWindow.

The extensibility of MapWindow is one reason why it was chosen as the GIS foundation for BASINS. MapWindow can be extended with plug-in components written in any Microsoft .NET language. The plug-in interface allows third-party developers to create plug-ins that become fully integrated into the BASINS interface. This means that third parties can write plug-ins to add additional functionality (models, special viewers, hot-link handlers, data editors, etc.) to BASINS and pass these tools along to other clients and cooperators.

For the large-scale model setup of the San Francisco Bay Area, a feature of MapWindow known as 'scripting' was key to developing model input files for all 22 sub-watersheds quickly and efficiently. A script consists of programming code stored in an ASCII file that is compiled at runtime, allowing the user an easy, dynamic method to assemble customized utilities. In MapWindow the user has a choice of writing code in one of two languages, VB.Net or C#. For this project a series of scripts were written to process GIS data and transfer parameter values from external databases into the model input files.

Prior to the use of the script, GIS functionality was used to develop a series of tables in a standard tabular file format. The tables used in this project included tables representing the area of each land use within each modeled sub-watershed, mean slope for each land use within each sub-watershed, precipitation and potential evapotranspiration multiplication factors and database connection information for each sub-watershed, upstream to downstream stream reach connectivity, hydrologic soil group for each sub-watershed, and stream characteristics (such as mean width, mean depth, length, slope, and contributing area). A table of parameter values was also prepared for a selected set of HSPF calibration parameters for a range of slope classifications and each of the hydrologic soil groups.

The model setup script for the Bay Area model reads the above-mentioned tables, creates a base HSPF user-control input file (UCI file) for each of the 22 sub-watersheds, and then modifies each UCI file as needed. Creation and modification of a UCI file through BASINS is relatively simple because properties of and methods for operating on a UCI in memory are available to a programmer through the BASINS open-source UCI object.

The modifications made to each UCI through the script include setting stream characteristics, computing a starting FTABLE (which defines the stage-surface area-volume-discharge relationship for a stream reach), setting the contributing area of each land use to each stream reach, making the proper meteorologic database connections, adding urban and agricultural irrigation to the simulation where desired, and setting specified model calibration parameters based on dominant hydrologic soil group and slope class. The script also handled establishing the upstream to downstream stream reach connectivity necessary for routing the flows and loads to the Bay.

Without the scripting capability of BASINS and MapWindow, producing the model inputs for a large-scale watershed model of this sort would have been much more difficult and would have required significantly more resources. The open-source architecture of BASINS provided the efficiency in the model setup process that was essential in delivering a product useful for producing loading results, which were then used to feed the Bay modeling component in the later stages of the larger study. The BASINS open-source GIS platform provided this avenue to develop extendible tools for mass production and modification of HSPF input files.

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