Guadalupe River Watershed Loading HSPF Model: Year 3 final progress report

Prepared by

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For

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ABSTRACT

San Francisco Bay, California is impaired with polychlorinated biphenyls (PCBs) and mercury (Hg). Environmental managers are interested in improving loads estimates from watersheds to the Bay, learning more about which land uses or source areas are responsible for loads generation, and how management can intervene to reduce loads. Through previous monitoring efforts, the Guadalupe River, draining to southern San Francisco Bay, was identified as supplying a disproportionately large load of Hg and PCBs to the Bay. The Hydrologic Simulation Program-FORTRAN (HSPF) was used to estimate sediment, mercury and PCBs loads moving through this mixed land use watershed as a tool for improved management. Model parameters for hydrology were widely available and were successfully calibrated to observed data at two tributary sites and validated at a downstream mainstem site. HSPF-specific parameters were developed for mercury and PCBs since they do not currently exist in the published literature. Current data limitations hindered the calibration of the sediment and water quality models to satisfactory performance levels, but future data collection efforts could overcome these barriers, leading to a model that could be used for forecasting loads and impacts of management actions.

INTRODUCTION

Background on Hg and PCBs in Bay Area/Guadalupe Watershed

Fishing advisories for San Francisco Bay were first issued in 1994, updated in 1999, and then again recently in 2011 warning those who catch and consume fish from the Bay to limit consumption due to adverse concentrations of mercury and polychlorinated biphenyls (OEHHA 1999, 2011). Hg and PCBs are also harmful to birds, mammals, and other wildlife, causing lower breeding, rearing and overall survival (Davis et al 2003; 2007). As a result, the state government of California has listed San Francisco Bay as impaired for Hg and PCBs. Total maximum daily loads (TMDL) reports have been written that call for identification of urban sources and reduction of loads of total Hg and PCBs by 50% and 90% respectfully. The Hg TMDL includes an analysis that links the reduction of total Hg load to a biological response (Austin and Looker 2006). While there are arguments that system complexities may confound this linkage, the implementation plans of the TMDLs include an analysis of high-leverage sources and processes. In the case of PCBs the linkage is more established (SFBRWQCB 2008), and, until improved information on biologically important forms of Hg becomes available, managers are making efforts to reduce total loads of both Hg and PCBs to the Bay.

In response, a number of loading studies have already been completed (McKee et al. 2006a; David et al. 2009; Gilbreath et al. in review; David et al. in review), the study on Guadalupe River is continuing, a further three are in progress, and more are planned. Environmental managers are interested in improving loads estimates from watersheds to the Bay, learning more about which land uses or source areas are responsible for loads generation, how management can intervene to reduce loads, and measuring loading trends in relation to management actions. In addition, models are being developed to support extrapolation of limited data to estimate regional scale loads, and to support the analysis of combination of management options. Guadalupe River Watershed Model represents the first in what is currently envisioned to be a suite of modeling efforts including watershed specific load models for management scenario testing (the Guadalupe sediment, Hg, and PCB model described here being the first) and a regional-scale annual time step spreadsheet model for regional scale loads estimation of multiple contaminants (Lent and McKee 2011).

Through previous monitoring efforts, the Guadalupe River, draining to southern San Francisco Bay, was identified as supplying a disproportionately large load to the Bay (Thomas et al. 2002; McKee et al. 2004, 2006b; Davis et al. 2007). Given known water quality issues in this watershed spanning many decades beginning when the mercury mines were decommissioned in the early 1970s, and the management of the watershed for water supply and flood conveyance, the watershed is extremely data rich. Managers are interested in using the model to improve loading estimates, especially during climatic conditions not yet observed, and to more accurately determine the current baseline average load. The modeling software chosen for this effort was Hydrologic Simulation Program-FORTRAN (HSPF).

Background on HSPF

The software Hydrological Simulation Program – FORTRAN (HSPF) is a comprehensive watershed model of hydrology and water quality (Bicknell 2001). HSPF is part of the EPA BASINS modeling system (USEPA 2001), a public domain software jointly supported and maintained by the U.S. EPA and the USGS. BASINS/HSPF is widely used across the United States for modeling hydrology and sediment transport in watersheds (Ackerman et al. 2005; Booth 1990; Fontaine and Jacomino 1997; Bledsoe and Watson 2001). The model has been widely used for nutrients (Bergman et al. 2002; Im et al. 2003; Moore et al. 1988; Shirian-Orlando and Uchrin 2007) but uses of the model in peer-review literature are more rare for trace metals and have mainly focused on copper, lead, and zinc (Ackerman and Stein 2008; Gersberg et al. 2000; Hummel et al. 2003). HSPF has been used locally in the San Francisco Bay Area for calibration models to parameterize the Bay Area Hydrology Model software for designing of development projects to minimize hydromodification impacts (AQUA TERRA Consultants 2006; Clear Creek Solutions, Inc. 2007), and to estimate the relative contribution of various anthropogenic sources of copper in stormwater runoff for the Brake Pad Partnership (Donigian and Bicknell 2007). In Southern California, HSPF was used to model mercury for TMDL linkage analysis (Larry Walker Associates, 2006). Thus far, no published studies have used HSPF to model PCBs, but several studies have used HSPF to model other organochlorine compounds, such as DDT (Dean et al. 1985) and atrazine (Parker et al. 2007). The use of the model for contaminants such as Hg and PCBs is novel and some parameters need further development.

METHODS

Study Watershed

The Guadalupe River watershed is located in the Santa Clara Valley basin and drains to Lower South San Francisco Bay (Figure 1). The watershed drainage area encompasses approximately 444 km^2 (170 mi^2) and an elevation change from sea level to nearly 1,160 m (3,800 feet). The watershed includes six reservoirs, which are located in the upper reaches of four of the tributaries in the watershed.

The watershed is approximately 46% developed urban area, 33% forest and 16% open area (Table 1). Only areas downstream from the reservoirs were dynamically simulated. Detailed land use statistics were also determined for this portion of the watershed (Table 1) and indicate the downstream portion of the watershed is mostly developed (75%), while the headwaters are mostly forested mountains.

The Guadalupe Watershed has a mild Mediterranean-type climate with a cool wet winter season around 16°C (60°F) and a warm dry summer season around 27°C (80°F). The lower elevation areas receive an average of 380 mm (15 inches) of rainfall per year, while the upper elevations annually receive 1,000-1,500 mm (40-60 inches) of precipitation. On average, >90% of the annual rainfall occurs from November to May inclusively but there is large inter-annual variability in rainfall, e.g., 40% to 200% of normal in the Bay Area (McKee et al. 2003), resulting in an annual runoff variation

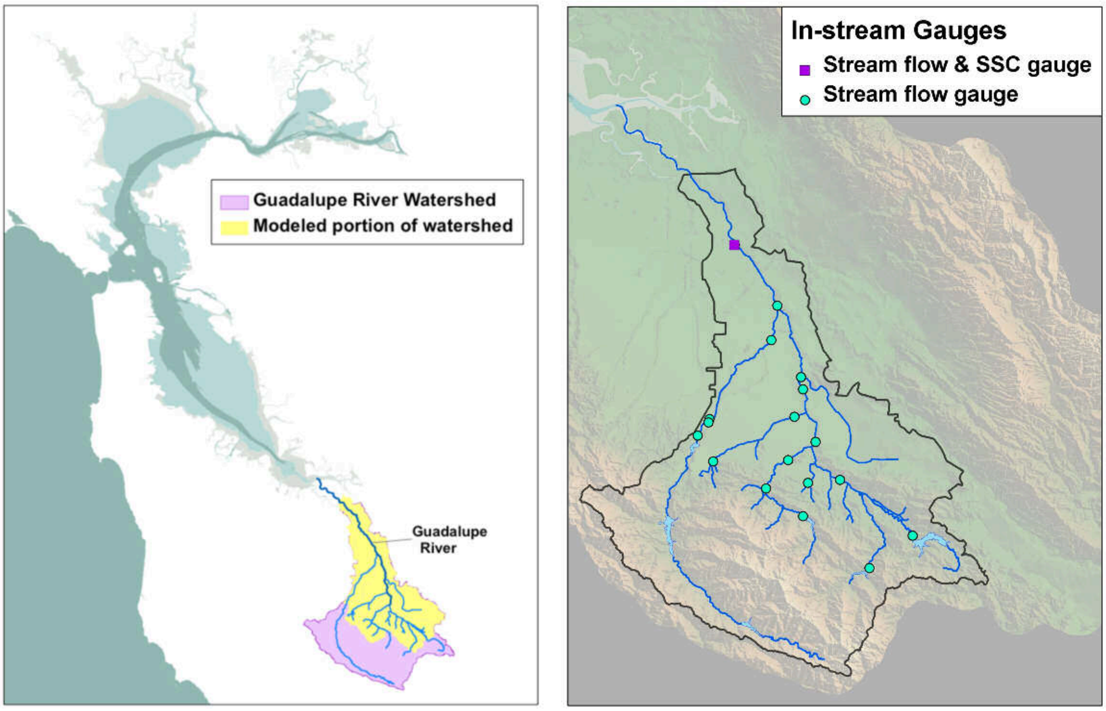

Figure 1. Guadalupe River Watershed: (a) Location, and (b) In-stream monitoring sites.

Table 1. Land Use Data and Estimated Imperviousness for the Guadalupe River Watershed Model.

Land Use	Estimated % Impervious	Entire Watershed Area [km^2] (% of total)	Modeled Area [km^2] (% of total)
Open	0%	72 (16%)	30 (11%)
Forest	0%	144 (33%)	25 (9%)
Agriculture	0%	14 (3%)	13 (5%)
Hg mining/furnace yard	0%	11 (2%)	11 (4%)
Residential - rural/low	5%	25 (6%)	23 (9%)
Residential - med./high	35%	104 (23%)	97 (37%)
Industrial	60%	23 (5%)	22 (8%)
Commercial/Public	75%	50 (11%)	44 (17%)
Total	-	443	265

during the period of USGS published record (1930-2009) of 1-560% of the long term average (43.2 million m^3).

The dominant soil texture in Guadalupe River Watershed is loam. The soil in the lower portion of the watershed is clay, while the rest of the watershed has a mixture of clay loam, silt loam, and loam (EOA, Inc. 2006). The local soil infiltration rates vary from moderate to very slow. The movement of soil in the Guadalupe River watershed is highly event driven. The majority of sediment discharge occurs during short-lasting, intense winter storms (Kroll 1975; McKee et al. 2003). On average, about 90% of the sediment load occurs during just a few days per year (Kroll 1975; Warrick and Milliman

2003; McKee et al. 2003; McKee et al. 2004). Suspended sediment concentrations are closely correlated with flow in part because the extensive dry season essentially returns the system to the same initial condition by the start of the wet season (Krone 1979). Suspended sediment load in the Guadalupe River watershed, like most watersheds in the Bay Area, appears to be transport-limited, rather than supply-limited.

Historic agricultural, mercury mining, and industrial activities and more recent urban development and population growth in the Guadalupe River watershed have resulted in widespread distribution of contaminant sources in the watershed. The inoperative mining district of New Almaden (within the Alameda Quicksilver County Park), which at one time was the largest supplier of mercury in North America, is responsible for historic deposits of mercury that continue to flow to the Bay from upstream areas via a drainage network (Thomas et al. 2002; Conoway et al. 2003). In addition, mercury from urban uses and atmospheric deposition continues from the lower urbanized and impervious areas of the watershed. Although PCB manufacturing was banned in the late 1970s, PCB use during the 1950s and 1960s in power transmission, capacitors, hydraulic fluids, plasticizers, paints, and flame retardants left a legacy of these long-lived compounds dispersed unevenly in urban environments (McKee et al. 2006b).

Model Description

The HSPF is a continuous, deterministic lumped-parameter model that simulates hydrologic and water quality processes on pervious and impervious land surfaces, in streams, and in well-mixed water bodies (Bicknell et al., 2001). The model generates a time history of the runoff flow rate, and sediment and contaminant concentrations for any point in the watershed being modeled.

The base modules of HSPF are PERLND, IMPLND, and RCHRES. PERLND represents pervious land, IMPLND represents impervious land, and RCHRES represents stream segments (reaches) and water bodies (reservoirs). The PERLND module calculates infiltration and soil moisture storage, while IMPLND does not. The RCHRES treats stream segments as uni-directional and one-dimensional (i.e. as a well-mixed stream with a uniform cross-section).

The key hydrologic processes are infiltration and surface runoff generated from precipitation and irrigation. Infiltration drives subsurface flow, which contributes to stream flow, along with the surface runoff. Precipitation and surface runoff drive soil/sediment detachment and transport. Suspended sediment is preferentially transported by grain-size to channels, where it can be carried downstream by advection or deposited locally to become bed sediment. Depending on the stream flow conditions and the shear stress levels, the bed sediment can accrete or erode. Contaminants can be modeled as runoff-associated or sediment-associated or as both (in this current application). The runoff-associated contaminant module functions as a basic build-up/wash-off model and can include both wet and dry atmospheric deposition. The sediment-associated contaminant module assigns contaminant concentrations to soil/sediment, which is transported by runoff to channels. Particle size distribution and preferential transport are implicitly incorporated by applying ratios to the sediment yield into channels. Once in-stream, clay, silt, and sand are modeled as separate constituents; however, bed load is not modeled explicitly. In-channel contaminants can be transported by advection, can be deposited or eroded (when sorbed to sediment), can undergo partitioning and decay processes. Several notable model simplifications for contaminant processes include no partitioning in surface runoff and no speciation for user-defined constituents.

The BASINS system was used to delineate the overall watershed boundary and the subbasin boundaries in the Guadalupe River Watershed using elevation from National Elevation Dataset, drainage maps from National Hydrography Dataset (NHD-Plus), and a local stormdrain catchment map and GIS data set developed by William Lettis & Associates, Inc. (WLA) in association with the Oakland Museum of California (OMC) and San Francisco Estuary Institute (SFEI). A major consideration in delineating in the watershed boundary was the presence of six reservoirs in the headwaters area of the watershed. To simplify the model, the watershed boundary was adjusted to exclude reservoirs and their upstream watersheds. Reservoir releases and loads were then included as point-source inputs into the appropriate stream locations. By delineating the watershed in this way, the model was able to account for the influence of managed reservoir flows without having to model the internal dynamics of the reservoirs themselves.

The Guadalupe River Watershed was subdivided into 12 model segments ("parameterization units") containing 27 subbasins. The subbasin boundaries were modified to coincide with monitored locations and areas of interest (e.g. former Hg mines and selected urban and non-urban areas). Land use, based on data sets from SCVWD and Association of Bay Area Governments (ABAG), was aggregated into nine categories: open, forest, agriculture, the historic Hg mining area (now the New Almaden Quicksilver County Park), the historic Hg furnace yard where the majority of ore was processed, rural/low-density residential, medium-/high-density residential, commercial/public, and industrial areas.

The contaminants were treated in a simplified manner in the model. Mercury exists in several forms in freshwater environments [Hg(0), Hg(II), and MeHg] and cycles between these species. In this model, all species were treated as an aggregate [total-Hg]. The chemical properties of Hg(II) were used for model parameterization since Hg(II) is the dominant species (>99%) of Hg in Guadalupe River (data not shown). PCBs exist as a mixture of 209 congeners, which are present in varying amounts in the environment, depending on amounts manufactured (and subsequently released to the environment) as well as congener persistence. In this model, PCBs were modeled as total-PCBs, i.e., sum of all congeners. The congener PCB-118, a pentachlorobiphenyl, was selected to provide representative properties as input to the model for several reasons: it has an intermediate chlorination level and, thus, intermediate chemical properties; it is abundant in Aroclor 1254, which is the predominant Aroclor in San Francisco Bay samples (Johnson et al. 2000); and it has similar chemical properties to PCB-126, the most toxic congener that is generally not measured due to its very low concentrations (Davis 2004).

Another model simplification was treating dissolved organic carbon (DOC) implicitly through incorporation into linear partition coefficients. In some Hg and PCBs watershed models (e.g. WARMF, DELPCB), DOC has been modeled explicitly since DOC concentrations normally have a strong impact on dissolved Hg and PCB concentrations. This relationship appears more valid for watersheds where atmospheric deposition is a major source of contamination and dissolved organic carbon plays a dominant role in transport of Hg (Hurley et al., 1998; Grigal, 2002). In the Guadalupe River, we find only weak relationships between DOC and Hg as well as PCBs. Perhaps because the majority of the mercury contamination is sediment-associated from mining sources and the majority of the PCB contamination is sediment-associated from industrial sources. Therefore implicit treatment of DOC through the use of partition coefficients appears reasonable for the Guadalupe River application.

Data Collation

Hydrologic model performance is highly dependent on the accuracy and quality of precipitation data. Especially in a watershed with large elevation changes (near sea-level to approximately 3000 feet in the modeled portion of the Guadalupe River watershed), rainfall tends to vary greatly with location and time. Therefore, high quality precipitation data with high temporal and spatial resolution were needed. Fortunately, the Guadalupe River watershed contained high-resolution rainfall gauges well distributed spatially and at a wide range of elevations.

High-resolution precipitation data (15-minute intervals) were obtained from Santa Clara Valley Water District (SCVWD) for five precipitation gauges located within the watershed and one gauge just outside. The time period of the rainfall data was chosen to overlap with Guadalupe River sediment and contaminant data sets. Hourly reference evapotranspiration data were obtained for Morgan Hill from California Irrigation Management Information Systems (CIMIS) and monthly pan evaporation data from the Los Alamitos Recharge Facility in San Jose were obtained from SCVWD.

Stream flow records (15-minute intervals) were obtained from the USGS and SCVWD for numerous gauges in the watershed (Figure 1) for October 1994 to September 2007. Additionally, reservoirs release and diversion records were obtained to use as point sources and sinks in the model. Another water source for the watershed was urban irrigation, however, irrigation time series data were not available and instead were estimated from precipitation and evapotranspiration records using methodology from AQUA TERRA Consultants (2006). Agricultural irrigation was not treated since less than 5% of the watershed is dedicated to agriculture.

Suspended sediment records (15-minute intervals) were obtained from SFEI and USGS for the wet seasons of water years 2003 to 2007 for the SSC gauge (USGS #11169025) (Figure 1). Additionally, sediment load time series were developed for the reservoirs as point sources into the model based on reservoir release grab samples collected for the Guadalupe TMDL (Tetra Tech, Inc. 2003). Unfortunately, no SSC records were available for the major tributaries.

Mercury and PCB concentration data for calibration and validation purposes were compiled from SFEI's Guadalupe River sampling program (e.g. McKee et al. 2006b). SFEI's Guadalupe River sampling program collected Hg and PCBs samples from WY2003-2006 and 2010 at the SSC gauge site (USGS #11169025) and at a second site upstream (USGS #11167800) during WY 2010 only (McKee et al. unpublished data). Water samples were collected using a FISP D-95 water quality sampler from bridges using a crane and winch during non-wading stages and by dipping clean prepared sample bottles below the surface in the deepest point of each stream location during wading stages. Roughly 90% of the samples were collected during storm flow. One liter samples for Hg analysis were analyzed for total Hg with cold vapor atomic fluorescence following U.S. EPA method 1631e (USEPA 2002) at San Jose State University Moss Landing Marine Laboratories. A subset of samples were also analyzed for dissolved mercury species. Four liter samples for PCBs were analyzed for 40 congeners using high-resolution gas chromatography / high-resolution mass spectrometry (HRGC/HRMS) following EPA method 1668 revision A (USEPA 1999) at AXYS Analytical Services Ltd, Sidney British Columbia, Canada.

Mercury load time series were developed for the reservoirs as point sources into the model based on reservoir release grab samples collected for the Guadalupe TMDL (Tetra Tech, Inc. 2003). Most of the grab samples were taken from low flow events (controlled releases). The reservoirs contributions of sediment and mercury during uncontrolled releases were a major data gap. During low flow releases, the reservoirs contributed little sediment-associated mercury since the most of the reservoir releases have very low sediment concentrations (1-10 mg/L); however the reservoirs were an important source of dissolved mercury into the watershed. PCB reservoir loads were not modeled due to PCBs' tendency to strongly sorb to sediment and the low sediment concentrations in the reservoir releases. Unfortunately, there were no data to support or contradict this assumption. Wet and dry atmospheric deposition sources were included for both mercury and PCBs (Tables 2 and 3). For mercury, local deposition data were available, but for PCBs, national data were used.

Initial Parameterization

To the extent possible, initial model parameters were obtained from literature, with preference given to local information. Initial hydrology parameters relied heavily on local HSPF hydrology modeling reports (Aqua Terra Consultants 2006; Clear Creek Solutions, Inc. 2007), as well as BASINS Technical Note 6: Estimating Hydrology and Hydraulic Parameters for HSPF (USEPA 2000). Initial sediment parameter data were based on local soil data (EOA 2006) and the HSPF Parameter Database (HSPFParm) (USEPA 1999), which had parameters for a watershed in the same county (Calabazas Creek, Santa Clara County, CA). Additionally, bed sediment grain-size data were obtained from USGS for the downstream gauge site.

Table 2. Parameter Values for Mercury Simulation.

Parameter	Description (units)	Values used	Ref.
POTFW	Detached sediment potency factor (lbs/ton)	$2*10^{-5}$ – 0.152	1; 2
POTFS	Soil matrix scour potency factor (lbs/ton)	$2*10^{-6}$ – 0.0152	1; 2
ACQOP	Rate of accumulation (lbs/ac*day)	$1*10^{-8}$ – $2*10^{-8}$	3
SQOLIM	Maximum storage (lbs/ac)	$1*10^{-6}$	3
WSQOP	Runoff value for 90% removal/hour (in/hr)	1.5	4
ADPM1	Linear partition coefficient (L/mg)	0.001 – 0.08	5; 6
ADPM2	Adsorption/desorption rate (1/day)	0.1 – 0.2	7
ADFX	Dry atmospheric deposition (lbs/ac*day)	$4.6*10^{-7}$	8
ADCN	Wet atmospheric deposition (mg/L in rain)	$9.7*10^{-6}$	8

1 – LWA 2006; 2 – Tetra Tech 2005; 3 – Gersberg et al. 2000; 4 – Carleton and Cocca 2004; 5 – Allison and Allison; 6 - Wetzel 2005; 7 – Aqua Terra 2009; 8 – Tsai and Hoenicke 2001

Table 3. Parameter Values for PCBs Simulation.

Parameter	Description (units)	Values used	Ref.
POTFW	Detached sediment potency factor (lbs/ton)	$4.4*10^{-6} – 8*10^{-4}$	1
POTFS	Soil matrix scour potency factor (lbs/ton)	$4.4*10^{-7} – 8*10^{-5}$	1
SQOLIM	Maximum storage (lbs/ac)	$1*10^{-6}$	2
ADPM1	Linear partition coefficient (L/mg)	0.00676 – 0.0676	3
ADPM2	Adsorption/desorption rate (1/day)	0.001 – 0.1	Calib.
FSTDEC	First order decay rate (1/day)	0.0057	4
KSUSP/KBED	Sediment-associated decay rate (1/day)	0.008	4
ADFX	Dry atmospheric deposition (lb/ac*day)	$1.2*10^{-7}$	5
ADCN	Wet atmospheric deposition (mg/L in rain)	$2*10^{-6}$	5

1 – McKee et al. 2006; 2 – Gersberg et al. 2000; 3 – Hansen et al. 1999; 4 – Mackay et al. 1992; 5 – Park et al. 2001

Since no HSPF parameter data are available for Hg or PCBs in the existing published literature, a broader literature search was performed to gather chemical properties data on each contaminant, as well as known and expected concentrations data for soils and sediments. The references for the parameters used are listed (Tables 2 and 3). For mercury, the model's soil and bed sediment components were parameterized using local data on mercury concentrations in soils and bed sediment from the Guadalupe TMDL (Tetra Tech, Inc. 2003). No data were found for PCBs in soils for Guadalupe Watershed, so the PCB model soil parameterization relied on a review of world literature on PCBs concentration in soils by land use category (McKee et al. 2006c). PCBs in bed sediment concentrations were guided by data on PCBs in bed sediment from a number of storm drainages in Santa Clara County (KLI 2002; Yee and McKee 2010).

Calibration and Validation Process

Calibration of a HSPF model is an iterative process of making parameter changes and sometimes model set-up changes, running the model and comparing the simulated model outputs to observed data or literature values. The standard procedure is to calibrate hydrology first, then hydraulics and sediment, and finally contaminants. The HSPF calibration procedure is well documented by Donigian (2002).

The hydrologic model was calibrated at two upstream locations and validated at the most downstream gauge. Two Guadalupe River tributaries with very different surrounding landscapes were chosen as upstream calibration sites. The first, Guadalupe Creek, flows from a steep undeveloped area. The second, Canoas Creek, flows through a mostly flat mixed-development area. Additionally, Guadalupe Creek is reservoir influenced whereas Canoas Creek is not reservoir influenced. The hydrologic model was calibrated using comparisons between observed and simulated instantaneous discharge at the hourly and daily time step, monthly and annual flow volumes, and long-term flow duration curves.

The hydraulic model was calibrated by comparing simulated and observed flow velocity and simulated and observed velocity-discharge relationships. Stage, velocity and discharge data were available for two locations on the Guadalupe River, allowing for calibration of the model's stage-volume-discharge tables for the main stem of the river. The data set was not large enough to validate the hydraulic calibration. Since no stage and flow velocity data were available for the tributaries, their stage-volume-discharge tables were adjusted according to expected behavior.

The sediment model was calibrated to a suite of local data, literature values and expected behaviors. The soil/sediment erosion model was calibrated to local estimates of sediment yields calculated for each model segment and land use. The sediment yield target values were based on local estimates of sediment production rates for different land use types (Lewicki and McKee 2009) that were scaled by an area-based delivery ratio. The in-stream sediment model was calibrated at the downstream site using comparisons between observed and simulated instantaneous suspended sediment concentrations at the hourly and daily time step and instantaneous grain size distributions. Suspended sediment data at the downstream site was available for WY2003-2007, and was split into WY2003-2005 for calibration and WY2006-2007 for validation. The sediment model was also calibrated to expected bed behavior for known areas of accretion or erosion. A major limitation in the sediment calibration data set was the lack of SSC records for the tributaries.

Similar to the sediment model, the contaminant models were calibrated to a combination of local data and data from published literature. The land-based contaminant models were calibrated to target Hg and PCBs yields calculated by land use (Mangarella et al. 2006). The in-stream contaminant models were calibrated to instantaneous suspended contaminant concentrations (grab sample data) and to bed sediment contamination data. For both Hg and PCBs, contaminant grab sample data were available for WY2003-2006, and were split into WY2003-2004 for calibration and WY2005-2006 for validation. For the calibration period, 62 Hg and 39 PCBs concentration data points were available. For the validation period, 101 Hg and 26 PCBs concentration data points were available. Additionally, Hg grab sample data were available for numerous upstream locations (e.g., all of the major tributaries to Guadalupe River) during the modeled period, although these were generally small data sets (2-25 samples). These upstream data sets provided spatial resolution and were used to refine the Hg calibration.

Model Evaluation

The model was evaluated using recommended statistical measures and performance metrics (Donigian 2002; Moriasi et al. 2007). The model was run on a 15-minute time step from WY 1995 to 2007 with the first year of data repeated as a spin-up year to initialize the model. The results of the spin-up year were excluded from the model evaluation. Calibration and validation statistics were calculated for daily flow volume and daily suspended sediment concentration. To better assess model accuracy, the performance was evaluated separately for storm events and baseflow conditions. For the contaminants, calibration and validation statistics were calculated for the paired simulated concentrations and grab samples (rounded to the nearest hour). Most of the grab samples were taken during storm events, so the data were not separated for storm events and baseflow conditions.

The following statistics were used to evaluate model performance:

- Coefficient of determination (R^2)
- Percent bias (PBIAS)
- Ratio of root mean square error to the standard deviation of measured data (RSR)
- Nash-Sutcliffe efficiency (NSE)

Donigian (2002) provided the following model evaluation criteria for the coefficient of determination for daily streamflow: above 0.8 is 'very good' model performance, between 0.7 and 0.8 is 'good' model performance, between 0.6 and 0.7 is 'fair' model performance, and below 0.6 is 'poor' model performance. Moriasi et al. (2007) established the following model evaluation guidelines for watershed simulations: model performance can be judged satisfactory if NSE > 0.50 and RSR ≤ 0.70, and if PBIAS ±25% for streamflow, PBIAS ±55% for sediment, and PBIAS ±70% for contaminants.

RESULTS AND DISCUSSION

Hydrologic Simulation

The hydrologic model calibration resulted in parameters being adjusted by land use type, hydrologic soil group and slope. The final calibrated key hydrologic parameters are shown Table 4 along with typical values for comparison. The statistical evaluation of the hydrologic model calibration and validation are shown in Table 5. For both the calibration and validation, the model exhibited satisfactory performance for storm events, meeting all model performance criteria from Moriasi et al. (2007). The model performed less well for baseflow conditions, but still met the satisfactory performance criteria for Guadalupe Creek and Guadalupe River. The model failed the satisfactory performance criteria for baseflow conditions for Canoas Creek. However, inspection of the Canoas Creek flow record showed the low-flow/dry season gauge records were unreliable, for example, occasionally early or late season storms were missed due to the gauge being offline or otherwise non-responsive.

For the watershed as a whole, the model simulated daily streamflow very well (Figure 2a), exhibiting a nearly 1-to-1 relationship with a coefficient of determination of 0.95. Additionally, the model was able to capture behavior of storms on an hourly basis (data not shown).

Table 4. Parameter Values for Hydrologic Simulation.

Parameter	Description	Values used	Typical range*
LZSN	Lower zone nominal storage (in)	4.0 – 14.0	3.0 – 8.0
INFILT	Soil infiltration capacity index (in/hr)	0.04 – 0.12	0.01 – 0.25
AGWRC	Groundwater recession coefficient (1/day)	0.92 – 0.99	0.92 – 0.99
UZSN	Upper zone nominal storage (in)	0.5 – 1.5	0.1 – 1.0
DEEPFR	Fraction of groundwater inflow to deep recharge	0.1 – 0.3	0.0 – 0.2
LZETP	Lower zone ET parameter	0.5 – 0.95	0.2 – 0.7
INTFW	Interflow inflow parameter	0.5 – 2.5	1.0 – 3.0
IRC	Interflow recession parameter	0.3 – 0.8	0.5 – 0.7
CEPSC	Interception storage capacity (in)	0.1 – 0.3	0.03 – 0.20

*from BASINS Technical Note 6 (USEPA 2000)

Table 5. Hydrologic Simulation Results: Comparing observed and simulated daily flow (cfs).

	WY 1995-2007	R^2	% Bias	RSR	NSE
Calibration site #1:	storm	0.86	-16	0.39	0.85
Canoas Creek	baseflow	0.37	-54	1.9	-2.6
Calibration site #2:	storm	0.88	19	0.44	0.81
Guadalupe Creek	baseflow	0.78	-0.9	0.47	0.78
Validation site:	storm	0.93	-10	0.27	0.93
Guadalupe River (USGS #11169025)	baseflow	0.78	-8.7	0.52	0.73

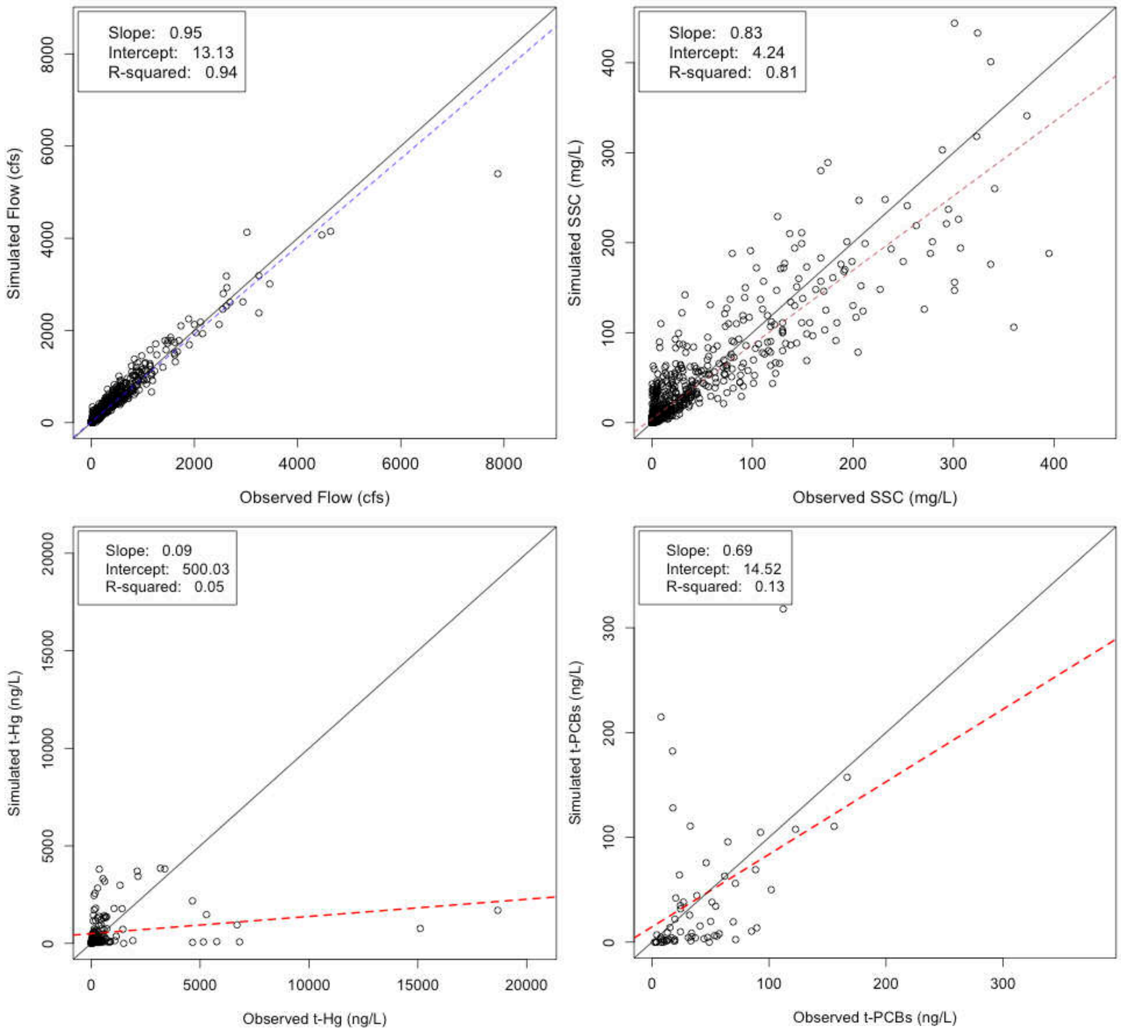

Figure 2. Comparison of Observed and Simulated Values: (a) Daily streamflow (WY1995-2007), (b) Daily sediment (WY2003-2007), (c) Mercury grab samples (WY2003-2006), and (d) PCBs grab samples (WY2003-2006).

Sediment Simulation

The sediment model calibration was limited to adjusting parameters to achieve general "expected behavior" in the tributaries and looking at overall results at the bottom of the watershed where data was available. The key sediment parameters used are shown in Table 6 along with typical values for comparison. The statistical evaluation of the sediment model calibration and validation are shown in Table 7. For both the calibration and validation, the model exhibited satisfactory performance for storm events, meeting all model performance criteria from Moriasi et al. (2007). The model performed poorly for baseflow conditions, exhibiting strong bias towards over-simulating sediment concentrations. Evaluating the sediment model over the entire period of data collection shows a large degree of scatter at the higher SSC values (Figure 2b), suggesting that the model is performing less well during storm events than the data in Table 7 would suggest.

Table 6. Parameter Values for Sediment Simulation.

Parameter	Description (units)	Values used	Typical range*
KRER	Coefficient in the soil detachment equation	0.25 – 0.30	0.15 – 0.45
JRER	Exponent in the soil detachment equation	2	1.5 – 2.5
AFFIX	Daily reduction in detached sediment (1/day)	0.0 – 0.05	0.03 – 0.1
COVER	Fraction of land surface protected from rainfall	0.60 – 0.97	0.0 – 0.90
NVSI	Atmospheric additions to sediment storage (lbs/ac*day)	0.0 – 2.0	0.0 – 5.0
KSER	Coefficient in the detached sediment washoff equation	0.4 – 2.0	0.5 – 5.0
JSER	Exponent in the detached sediment washoff equation	2	1.5 – 2.5
KGER	Coefficient in the soil matrix scour equation	0.0- 0.06	0.0 – 0.5
JGER	Exponent in the soil matrix scour equation	1.0	1.0 – 3.0
KEIM	Coefficient in the solids washoff equation	0.5	0.5 – 5.0
JEIM	Exponent in the solids washoff equation	2.0	1.0 – 2.0
ACCSDP	Solids accumulation rate on impervious surface (lbs/ac*day)	0.001 – 0.01	0.0 – 2.0
REMSDP	Fraction of solids removed per day	0.03 – 0.05	0.03 – 0.2
KSAND	Coefficient in the sandload power function	0.15 – 0.3	0.01 – 0.5
EXPSAND	Exponent in the sandload power function	2.1 – 3.0	1.5 – 3.5
W	Fall velocity in still water (in/s)	0.00004 – 0.0012	0.0001 – 4.0
M	Erodibility coefficient of the sediment (lbs/ft^2*day)	0.01	0.01 – 2.0
TAUCD	Critical bed shear stress for deposition (lbs/ft^2)	0.08 – 0.27	0.01 – 0.30
TAUCS	Critical bed shear stress for scour (lbs/ft^2)	0.18 – 0.32	0.05 – 0.50

*from BASINS Technical Note 8 (USEPA 2006)

Table 7. Sediment Simulation Results: Comparing observed and simulated daily suspended sediment concentrations (mg/L).

		N	R^2	% Bias	RSR	NSE
Calibration	storm	145	0.73	-11	0.55	0.70
(WY 2003-05)	baseflow	554	0.50	-134	1.18	-0.38
Validation	storm	120	0.81	-23	0.49	0.76
(WY 2006-07)	baseflow	335	0.66	-130	1.00	0.01

Contaminant Simulation

Due to the strongly sediment-associated nature of both mercury and PCBs, model calibration was hindered by the poor performance of the sediment model. Without confidence in the underlying model driving the contaminant transport, any calibration adjustments might be compensation for problems in the underlying model. Tables 2 and 3 provide the key parameters for mercury and PCBs, respectively. For the reasons explained above, parameters were not modified from literature values. Tables 8 and 9 document the poor performance of the contaminant models; in all years evaluated the Nash-Sutcliffe efficiency is below zero, which means the simulated values are worse predictors than the average of the observed data points. Figures 2c and 2d show the linear regression of each contaminant model over the entire period of data collection. The mercury model exhibits an extremely poor regression relationship in part due to two unusually high Hg grab sample values (both are from December 2002 when there may have been mass wasting events in the former Hg mining area). The PCB model exhibits a better regression relationship, but still there is a large degree of scatter in the relationship.

Table 8. Mercury Simulation Result: Comparing observed grab samples and corresponding simulated values (ng/L).

	Water Year	N	R^2	% Bias	RSR	NSE
Calibration	2003	26	0.02	70	1.14	-0.29
	2004	36	0.25	-40	2.20	-3.85
Validation	2005	52	0.001	-63	2.04	-3.16
	2006	49	0.03	-94	2.52	-5.37

Table 9. PCBs Simulation Results Comparing observed grab samples and corresponding simulated values (ng/L).

	Water Year	N	R^2	% Bias	RSR	NSE
Calibration	2003	21	0.03	34	1.51	-1.27
	2004	18	0.42	33	1.58	-1.49
Validation	2005	12	0.11	-43	1.59	-1.52
	2006	14	0.08	-108	2.58	-5.66

CONCLUSIONS

A high-resolution hydrology model was successfully developed for the Guadalupe River Watershed. The hydrology model was then extended to include sediment, but was hindered by a lack of calibration data in the tributaries. Initial parameters for mercury and PCB models were developed and applied to the (unsatisfactory) sediment model. As both contaminant models were reliant on the sediment model, their calibration and performance were limited by the sediment model needing improvement. If the sediment model were improved to satisfactory state, the contaminant models could be re-visited and potentially improved to an acceptable level of performance to forecast loads and impacts of management actions.

Recommendations

The recommendations for improving the model for both sediment and contaminants are to collect supporting data related to hydraulics, concentrations, and grain-size distribution and to have the model reviewed by an expert in sediment transport. Specifically, the ideal data set to support improvement of the model would be:

- stream cross-sections and stage-area-discharge-velocity relationships for all major tributaries
- SSC data for major tributaries (at minimum should have SSC data for reaches representing different sediment transport types, e.g., reservoir-fed steep reaches, non-reservoir-fed steep reaches, flatland reaches, urban reaches)
- sediment grain size data for reaches representing different sediment transport types
- sediment and contaminant concentration data for high-flow reservoir releases/spills
- generally improve local data sets for PCBs in relation to soils, and for PCBs and Hg in relation to grain sizes in both bed sediment and suspended sediment in flowing water.

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