Evaluating HSPF runoff and water quality predictions at multiple time and spatial scales

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ABSTRACT

Watershed models are widely used to describe runoff dynamics and associated pollutant loadings, but are rarely tested for accuracy. This study evaluates the accuracy of the Hydrological Simulation Program - FORTRAN (HSPF) model for predicting concentrations and loads of total suspended solids, copper, and fecal bacteria in Ballona Creek, an arid, highly-impervious, urban watershed with dynamic flows that can increase by three within an hour due to stormwater runoff. The model was calibrated by collecting data at sub-hourly intervals from small homogeneous land use sites and then validated with sub-hourly data collected at an instream site that received cumulative discharges from 74% of the watershed. Validation data were collected for seven storms ranging from one-half to three times the median storm size. The average storm load prediction error for hydrology was 24% with bias of only -1%. The error rate was higher for the constituents, but in all cases less than twice the error for hydrology. Predictions for constituent concentration at any time within the storm were generally within 75% of measured, though mistiming of the hydrograph led to overpredictions of constituents in the early part of two of the validation storms. The study's results suggest that constituent modeling is feasible even on short time scales and that the greatest gains in future model refinement will come from improving the hydrological component of the model. Constituent predictions would also be improved by a better approximation of the way in which runoff dynamics are partitioned between particulate and dissolved phases.

INTRODUCTION

Watershed models have been widely used for hydrological management. They have been applied to determine the effects of irrigation withdrawals on base flow conditions (Berris *et al.* 2001, Gosain *et al.* 2005). They have also been used to estimate the increase in stream flow and peak storm flows in urbanizing areas (Ng and Marsalek 1989, Brun and Band 2000, Bosch *et al.* 2003).

Increasingly, these models are also being used as water quality management tools. They allow assessment of which land use types within the watershed provide the greatest contribution to pollutant loading (Im *et al.* 2003). They also allow assessment of alternative management strategies, such as upstream source reduction, detention or downstream withdrawal and treatment (Moore *et al.* 1992, Cryer *et al.* 2001, Coon 2003, Albek *et al.* 2005).

Water quality applications are inherently more difficult than hydrology applications, particularly when implemented on intra-storm time scales that allow assessment of management options for treating or removing water from a portion of a storm. Short time scale applications are particularly difficult to implement for water quality parameters because of the necessary data density. Whereas automated gauges provide continuous data for hydrologic applications, most water quality parameters must be measured manually. As a result, these models are typically calibrated with storm event mean concentration data collected by periodic grab samples, without characterizing water quality changes throughout the event (Moyer and Hyer 2003, Im *et al.* 2004). In addition, water quality applications of these models are also complicated by biochemical processes that affect pollutant concentration, which can be more difficult to model than the physical factors governing hydrology.

While there are many studies validating use of watershed models for water quantity applications, validation of water quality applications are fewer and primarily limited to the grey literature. When validations have been performed, they have been conducted generally at storm-average or annual scales (McPherson *et al.* 2002). Furthermore, few of these applications have been in the arid southwest, where modeling is complicated by episodic events. Flow in arid watersheds is typically low or nonexistent between storms, but increases by an order of magnitude within hours and often recedes to baseflow in less than one day (Leecaster *et al.* 2002). Water quality also changes rapidly during these periods of dynamic flow (Stein *et al.* 2005).

This study investigates the Hydrological Simulation Program—FORTRAN's (HSPF) performance in accurately modeling total suspended solids (TSS), copper, and bacteria at short time intervals in Ballona Creek, a highly impervious watershed that drains urban Los Angeles. The modeling effort builds upon a previous hydrodynamic validation conducted in this watershed (Ackerman *et al.* 2005) to assess the additional error introduced when modeling chemical and biological parameters. These three constituents were selected because they differ in their sources and level of modeling complexity. Suspended solids are a natural part of the landscape and respond primarily to physical factors. Copper is more complex because it partitions between dissolved and particulate form, where it is bound to suspended solids. In addition, there are many anthropogenic sources of copper, consequently copper concentration in runoff varies during the course of a storm. Bacteria are even more challenging as they not only partition between the free and adsorbed state, but also are subject to biological decay (Noble *et al.* 2004).

METHODS

Ballona Creek is a highly developed watershed comprising a large section of the municipal Los Angeles area. Approximately 90% of this watershed is developed urban space; Ballona Creek (338 km^2) is the largest watershed draining to Santa Monica Bay, CA.

The watershed averages 20 storms and 34 cm of precipitation per year (Ackerman and Weisberg 2003). Portions of the upper watershed receive as much as 53 cm annually, mostly due to orographic differences on south facing slopes of the coastal foothills (Daly and Taylor 1998). Seventy percent of the annual rainfall occurs between January and March, with virtually no rain from May through October (Ackerman and Weisberg 2003).

Data sources

HSPF predicts flow based primarily on rainfall, land use characteristics, and stream geometry. Rainfall data for the Ballona Creek watershed were obtained from Los Angeles County Department of Public Works (LACDPW) Gage 10A, Los Angeles International Airport (LAX), and the University of Southern California (USC; LACDPW 2003; NCDC 2004). Rain data for land use catchments were obtained from nearby gages supported by LACDPW, or by deployment of rain gages at each of the land use sites. All gages measured rainfall in 0.254 mm increments.

Detailed land use data were obtained from the Southern California Association of Governments (Southern California Council of Governments 1993). Land use data were aggregated to seven categories (agricultural, commercial, high density residential, industrial, low density residential, open, mixed urban) based on similarity among 36 subcategories. Minimum land use resolution was 8 m^2. Table 1 presents the percent of perviousness for each land use, as established by LACDPW (DePoto *et al.* 1991).

Soil characteristics for the study areas were determined by downloading the Soil Survey Geographic data set (SSURGO) from the Natural Resources Conservation Service (Natural Resources Conservation Service 2005a). Annual soil loading rates were determined for the type of soils in the open land use areas using the Revised Universal Soil Loss Equation, Version 2 (RUSLE2) program (Foster *et al.* 2003), in addition to available data for Los Angeles County from (Natural Resources Conservation Service 2005b).

Streams in the Ballona Creek watershed are concrete-lined trapezoidal or rectangular channels. Stream geometry was defined using as-built engineering drawings (LACDPW 1999). Continuous flow data from Ballona Creek were obtained from an established gage maintained by the LACDPW (2003). At each of the land use sites, flow was also measured for specific storm events using area-velocity sensors and/or bubblers, each with automated data loggers.

Table 1. Land use aggregation and estimated perviousness for Santa Monica Bay.

Aggregated Land Use	Percent Pervious
Agriculture	94
Commercial	15
High-Density Residential	40
Industrial	25
Low-Density Residential	60
Mixed Urban	50
Open	97
Water	100

Water quality was incorporated into the model by adding land-use specific runoff coefficients to the hydrographs for those land uses. These data were obtained with a targeted sampling program to develop time-concentration series for TSS, copper, and fecal coliform. Twenty-one site events were sampled from six land uses (agriculture, commercial, high density residential, industrial, low density residential, and open) over a four-year period. Rainfall quantity ranged from 2.03 mm to 32.5 mm per event, and antecedent dry days varied from 3 to 31 days. The single land use catchments ranged from 0.02 to 9.49 km^2. Approximately 10 samples were collected per storm event to characterize changes in water quality during the different phases of the storm (Leecaster *et al.* 2002). Additional details of this targeted sampling effort can be found in Schiff and Sutula (2004) and Stein *et al.* (2005).

HSPF can also incorporate non-storm inputs from anthropogenic-derived baseflow. Baseflow was assumed to be 0.085 cms, evenly distributed from all Ballona Creek sub-basins. This baseflow is comprised entirely of non-point source anthropogenic inputs (such as lawn irrigation, car washing, sidewalk hosedown, etc.) and was extrapolated from average daily flow measurements from June through August 1977 to 1999, at the Sawtelle flow gage. The water quality concentrations assigned to dry season non-point sources was derived from long-term monthly monitoring conducted by the City of Los Angeles and two summer, low-flow surveys, finding TSS = 14 mg/L, copper = 7 µg/L, fecal coliform = 1600 cfu/100 ml (Stein and Tiefenthaler 2004).

Model calibration

The model was developed in three steps. The first step was calibration of the hydrologic component using model coefficients developed during a previous study (Ackerman *et al.* 2005). In that effort, a decadal simulation of hydrology was calibrated and validated for WY1990-1999 at Ballona Creek and nearby, less developed Malibu Creek watershed. The model evaluation used the first five years of the simulation for calibration with respect to identical model coefficients, and the second five years for validation. The daily average storm flows calibrated and validated reliably, with correlation coefficients greater than 0.8.

The second developmental step was calibration of suspended solids, which was accomplished by reproducing time-concentration series at small, homogeneous land use sites. Decadal simulations were conducted for two open land use catchments in order to capture a range of annual conditions in conjunction with simulation of monitored events at each site. Pervious area coefficients were adjusted to approximate the 0.25 kg/m^2/year loading from Cotharin clay loam and Sumiwawa-Hipuk soils and to match the concentration time series recorded for the two open land use sites. Sediment washoff was modeled within one class since there was insufficient data to properly characterize the washoff sediment distribution and the majority of the land use sites and Ballona Creek were concrete-lined with little sediment bed load. The calibrated pervious sediment parameters were applied to impervious open areas, as well as to the pervious areas of the other land uses (Table 2).

Sediment parameters for impervious land use areas were then calibrated by adjusting the solids transport parameters and the accumulation/removal rates. The accumulation/removal rates were assigned a ratio of 0.5 to reflect a 30-day buildup of surface saturation and a surface load of 0.5 tons/acre (Tiefenthaler *et al.* 2001). Land use calibrations were performed by comparing measured and modeled concentrations throughout the storm, as well as comparing loads and event mean concentrations (EMCs). Model parameters for the impervious areas are given in Table 3.

The third step was the generation of copper and bacteria models, which was accomplished by applying a potency factor to TSS. Copper was assumed to be particulate-bound and linearly related to TSS during washoff via potency factors. Data from the pollutograph sampling confirms the validity of this assumption (Figure 1). Fecal coliform was assumed to be approximately equally distributed between adsorbed and free forms (Characklis *et al.* 2005), so potency factors, buildup and the asymptotic limit were adjusted to maintain that balance, respectively. The asymptotic limit was set at 1.8 times the buildup based on United States Environmental Protection Agency (USEPA; 2000) guidance. The asymptotic limit was reached at three days, which was consistent with bacterial rainfall-runoff relationships seen in Ackerman and Weisberg (2003). Following the sediment calibration approach, the pervious areas were calibrated first for the open sites, then applied universally to the other land uses. The development of the land use impervious model parameters for copper and

Table 2. HSPF model coefficients for the pervious areas.

Parameter Description	Model Parameter	Value	Units
Supporting management practice factor	SMPF	1.0	none
Coefficient in the soil detachment equation	KRER	0.23	complex
Exponent in the soil detachment equation	JRER	2.0	complex
Fraction by which detached sediment storage decreases each day as a result of soil compaction	AFFIX	0.005	/day
Fraction of land surface which is shielded from rainfall erosion	COVER	1.0	none
Coefficient in the detached sediment washoff equation	KSER	1.8	complex
Exponent in the detached sediment washoff equation	JSER	2.0	complex
Coefficient in the matrix soil scour equation	KGER	0.0	complex
Exponent in the matrix soil scour equation	JGER	2.0	complex
Initial storage of detached sediment	DETS	1.12	tonne/ha
Washoff potency factor (copper)	POTFW	0.25	kg/tonne
Washoff potency factor (fecal coliform)	POTFW	1.11e11	colonies/ tonne
Rate of accumulation	ACQOP	2.76e8	colonies/ ha/d
Maximum storage	SQOLIM	4.96e8	colonies/ha
Rate of surface runoff which will remove 90 percent of stored constituent per hour	WSQOP	2.54	mm/hr

fecal coliform followed same process as the sediment calibration (Table 3).

Model validation

Model validation was accomplished by comparing concentrations throughout the measured events, storm loads and storm EMCs at a mainstem site in Ballona Creek. This site, which was located at the most downstream location where a flow gage was operated, included 74% of the watershed in its drainage. This site was sampled for TSS, bacteria and copper during seven storms, with ten samples collected throughout the course of each storm. The parameters developed in the model calibration were applied to the Ballona Creek watershed and compared to the measured concentrations. Error was calculated as bias, the average difference between measured and predicted, and as average absolute error, the average of the absolute values of the difference between measured and predicted values.

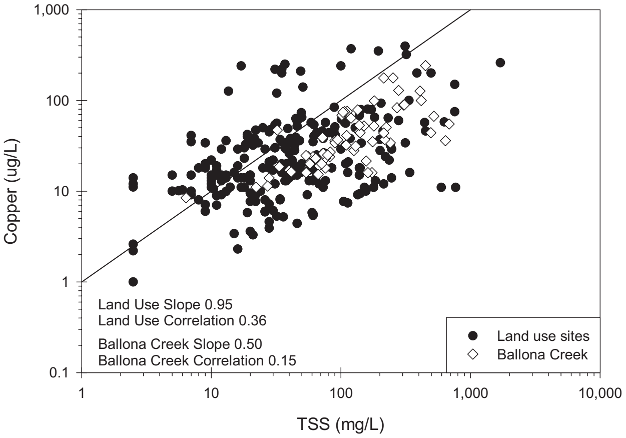

Figure 1. Relationship between measured TSS and copper concentrations for the monitored land use sites and Ballona Creek.

RESULTS

Calibration

The model calibration consistently reproduced the observed loads for individual land use sites (Table 4). The overall error for hydrology was 39%, but the bias was only -2%. Calibration for water quality constituents was less consistent, but was still reasonable. Absolute error for TSS loads across all land uses was 71%, with a bias of 12%, though the error for individual storms ranged as high as 200%. The absolute error for copper and fecal coliform was

Table 3. HSPF model coefficients for the impervious areas.

Parameter Description	Model Parameter	Units	Agriculture	Commercial	High Density Residential	Industrial	Low Density Residential	Mixed Urban	Open
Coefficient for transport of solids	KEIM	complex	0.1	0.03	0.2	0.15	0.4	0.05	0.2
Exponent for transport of solids	JEIM	complex	2.0	1.5	2.0	1.5	2.0	2.0	2.0
Accumulation rate of the solids storage	ACCSDP	tonne/ha/ day	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Unit removal rate of solids in storage	REMSDP	/day	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Sediment annual load*		kg/ha/year	4.23	0.97	2.20	1.64	2.99	2.46	4.35
Copper									
Washoff potency factor	POTFW	kg /tonne	0.30	0.5	0.30	0.15	0.15	0.4	0.075
Copper annual load*		kg/ ha/year	0.65	0.40	0.52	0.33	0.49	0.52	0.65
Fecal Coliform									
Washoff potency factor	POTFW	colonies/tonne	1.10e11	4.41e11	9.92e11	2.20e10	6.61e10	1.10e12	8.82e10
Rate of accumulation	ACQOP	colonies/ha/d	1.10e10	1.10e09	9.92e08	1.10e08	5.51e08	2.21e09	2.76e08
Maximum storage	SQOLIM	colonies/ha	1.98e10	1.98e09	1.76e09	1.98e08	9.92e08	3.97e09	4.96e08
Rate of surface runoff which will remove 90 percent of stored constituent per hour	WSQOP	mm/hr	2.54	2.54	2.54	2.54	2.54	2.54	2.54
Fecal coliform annual load*		colonies/ ha/year	9.42e11	4.26e11	1.23e12	2.71e11	6.35e11	1.01e12	9.59e11

*annual load was calculated by simulating each land use for a decade (WY 1990 —1999) and averaging the loads

Table 4. Predicted model load bias for the land use sites. The average calibration error was calculated as the absolute value of the error associated with each land use.

Average Absolute Error

Land Use	Volume	TSS	Copper	Fecal Coliform
AG	39 %	71 %	83 %	85 %
COM	24 %	40 %	17 %	77 %
HDR	22 %	87 %	36 %	116 %
IND	24 %	7 %	6 %	35 %
LDR	36 %	112 %	69 %	50 %
OPEN	76 %	73 %	73 %	94 %
Average	**39 %**	**71 %**	**83 %**	**85 %**

Average Error Bias

Land Use	Volume	TSS	Copper	Fecal Coliform
AG	-4 %	-11 %	-32 %	-34 %
COM	24 %	40 %	14 %	32 %
HDR	-8 %	-39 %	36 %	116 %
IND	-24 %	-7 %	-6 %	20 %
LDR	36 %	112 %	69 %	21 %
OPEN	-76 %	-73 %	-73 %	-94 %
Average	**-2 %**	**12 %**	**12 %**	**22 %**

Table 5. Predicted event mean concentrations and bias for the land use sites. The average calibration error was calculated as the absolute value of the error associated with each land use.

Average Calibration Error

Land Use	Hydrology	TSS	Copper	Fecal Coliform
AG	39 %	45 %	47 %	79 %
COM	24 %	21 %	16 %	85 %
HDR	22 %	45 %	44 %	123 %
IND	24 %	13 %	14 %	42 %
LDR	36 %	77 %	30 %	44 %
OPEN	76 %	32 %	12 %	29 %
Average	**39 %**	**43 %**	**30 %**	**74 %**

Average Calibration Bias

Land Use	Hydrology	TSS	Copper	Fecal Coliform
AG	-4 %	-7 %	-34 %	-29 %
COM	24 %	15 %	-10 %	8 %
HDR	-8 %	44 %	44 %	123 %
IND	-24 %	13 %	14 %	40 %
LDR	36 %	76 %	30 %	29 %
OPEN	-76 %	3 %	4 %	-29 %
Average	**-2 %**	**30 %**	**10 %**	**32 %**

Table 6. Load error at the Ballona Creek validation site for each storm.

Storm Date	Volume	TSS	Copper	Fecal
02/19/01	-1%	72%	55%	44%
04/07/01	-22%	-12%	-2%	-51%
11/24/01	-31%	-58%	16%	-11%
05/02/03	64%	104%	58%	3%
10/31/03	17%	-3%	-42%	No data
02/02/04	-23%	-14%	10%	-38%
02/21/04	-8%	12%	47%	-29%
Average absolute error	**24%**	**39%**	**33%**	**29%**
Average error bias	**-1%**	**15%**	**20%**	**-14%**

even greater, 83% and 85% respectively, across all land uses. However, bias for copper and fecal coliform was only 12% and 22% respectively.

Absolute calibration error for EMCs was less than that for loads, with bias only slightly higher (Table 5). The open areas had the highest observed TSS, lowest copper, and generally lowest fecal coliform concentrations. Modeled EMCs from the other land uses were also favorably comparable to observed EMCs; however, average bias for TSS and copper were both approximately 30%.

The model also calibrated well for the within-storm concentration time-series at the individual land use sites. There was no bias in the volumetric simulation, but there was a slight (24%) average overprediction. The TSS simulations tended to overpredict (66% over) the measured concentrations throughout the events, but the average concentration differences were always within an order of magnitude of measured. The copper simulations compared to measured values better than to TSS, with no bias in over- or under-prediction, and were on average within 50% of the measured values. The bacteria simulations had the largest discrepancy compared to the measured, but again demonstrated no consistent bias. Eighty percent of the predicted bacteria concentrations were within an order of magnitude of the measured concentrations.

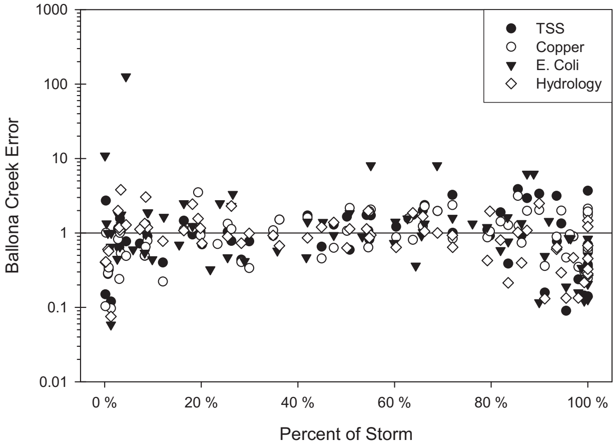

Figure 2. Error (modeled divided by measured) of the measured flow and water quality throughout the concentration time series at the Ballona Creek validation site.

Validation

The watershed model generally predicted loading estimates more reliably at downstream validation sites than at individual land use sites used to calibrate the model (Table 6). Average absolute error for hydrology was 24%, with a bias of only -1%. The error rate was higher for constituents, but in all cases less than twice the error rate for hydrology. Bias exceeded 10% for all constituents, though for only two of the storms did any constituent have an error of more than 50%.

The errors associated with EMCs were generally greater than errors for loads (Table 7). Both bias and error associated with EMC were greatest for copper; however, even for this constituent, the modeled EMC was within 50% of measured for most storms. For TSS, modeled was within 20% of measured for five of the seven validation storms.

The within-storm concentration time-series predictions for the Ballona Creek validation site were better than for the land use calibration sites (Figure 2), probably reflecting the averaging of errors across multiple land uses. Volumetric predictions were consistently within 50% of measured. Average TSS predictions in the first half of the storm were, overall, underpredicted measured by 4%, and increased to an overprediction of 50% in the latter half of the

Table 7. Event mean concentration error at the Ballona Creek validation site for each storm.

	TSS (mg/L)		Copper (ug/L)		Fecal Coliform (MPN/100ml)	
Storm Date	Measured	Modeled	Measured	Modeled	Modeled	Modeled
02/19/01	91	156	29	45	9,713	14,144
04/07/01	107	121	27	35	18,736	11,817
11/24/01	55	93	55	93	34,770	44,920
05/02/03	102	127	44	42	21,356	13,474
10/31/03	203	167	112	56		
02/02/04	213	237	51	72	38,019	30,480
02/21/04	95	116	24	39	14,897	11,430
Average absolute error	**29 %**		**44 %**		**32 %**	
Average error bias	**13 %**		**28 %**		**-7 %**	

storms. Copper predictions showed no bias in model predictions with the measurements underpredicting concentrations by 7%; however, one sample point was not included because mis-timing of the beginning of one storm resulted in a measured concentration less than 0.04 µg/L and the modeled of 34 µg/L. Bacteria compared well throughout the sampled storms with all but three modeled points within an order of magnitude of measured. Of those three points, two samples were from a storm where mistiming of the time series initiation resulted in measured concentrations for the first two samples of ~300 MPN/100 ml and modeled concentrations of 4,000 and 39,000 MPN/100 ml, respectively.

DISCUSSION

HSPF water quality simulations are founded on hydrology, with any errors in that module propagated into estimates for constituents. For this reason, the hydrology prediction errors were less than that of the chemical and biological constituents. However, for all constituents, the average error was less than twice that of the hydrology error. Thus, although there are inaccuracies in constituent modeling, the greatest potential for gain in model refinement still lies in improvement of the hydrological component of the model.

Ackerman *et al.* (2005) suggests that improving rainfall input data would provide the greatest advancement in HSPF modeling, which is consistent with our results. Early calibration efforts relied on the nearest existing rain gages to characterize rainfall in the catchment. In some cases, these gages were located several kilometers away from sampling points, leading to mistimed model predictions for the hydrograph and constituent loading. In subsequent sampling efforts, co-located rain gages were deployed at sampling locations to better represent local rainfall, resulting in vastly improved calibration.

While model validation focused on storm totals, the model also reliably predicted constituent concentrations during the course of the storms. The largest within-storm prediction errors were in the early part of the storms, specifically for two events. These errors appear to be primarily related to hydrological predictions that were mistimed by approximately one hour in the early part of the storm, possibly due to spatial and temporal coarseness of the rainfall input data. Within-storm predictions can be important because many management scenarios that might be evaluated using the model, such as detention ponds or increasing infiltration through removal of impervi-

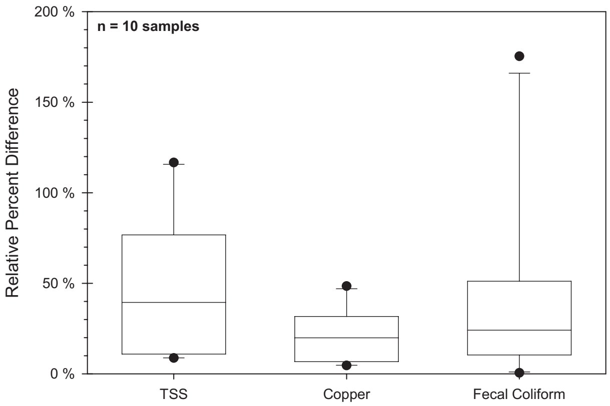

Figure 3. Difference in water quality concentration between duplicate stormwater samples for TSS, copper, and fecal coliform.

ous surface, are based on removal of constituents from a limited portion of a storm's runoff.

While model prediction errors for the constituents were relatively small, even apparent model prediction errors for the constituents must be considered in context of uncertainty in the validation data set. The validation data are a set of point measurements that include inaccuracies associated with small-scale spatial variability and laboratory measurement error. Laboratory measurement error alone for bacterial concentration has been shown to be typically 50% of the measured value (Griffith *et al.* 2006). To quantify precision of the validation data set, duplicate samples were collected in a nearby watershed for one of the storms. It was found that difference between replicates was greatest for TSS, with a median difference of approximately 50% (Figure 3). Between replicate differences were lowest for copper, with differences of only approximately 25%. Median differences in concentration between replicates for bacteria were intermediate for the other constituents, but differences of more than 200% were found for several paired samples. When these uncertainties in the validation are accounted for, the inclusion of constituents into the model adds only approximately 25% to the inaccuracies associated with hydrology and reinforces the concept that the greatest investment for improvement of the model will be in improving hydrological predictions.

While improving hydrology would be a good investment in future model refinement, there are also investments that would improve modeling of the constituents. For example, the model presently includes broad assumptions about particle washoff dynamics (fixed washoff ratio, no deposition/scour) that should be tested in the field. Also, a better approximation of the way in which runoff dynamics are partitioned between particulate and dissolved phases for various constituents would likely reduce error, as would an understanding of the way in which particle size changes throughout storms. In addition, measuring the sorbed and dissolved (free) copper and bacteria with varied particulate sizes, combined with the deposition/scour information, will enhance the model's predictive ability.

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ACKNOWLEDGMENTS

The authors would like to thank Jay Shrake, Sean Porter, Richard Rusnik, and the rest of the MacTec Engineering field crews for their assistance and dedication in collecting the stormwater samples. Funding for this study was provided by the Los Angeles Regional Water Quality Control Board, Western States Petroleum Association, Los Angeles Contaminated Sediments Task Force, City of Los Angeles, Los Angeles Department of Water and Power, Los Angeles County Sanitation Districts and the City of Carson. The authors also thank Tony Donigian of AQUA TERRA Consultants and Steve Carter of Tetra Tech, Inc. for their helpful comments on the manuscript.