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EVALUATING HSPF IN AN ARID, URBANIZED WATERSHED[1]

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ABSTRACT: The Hydrologic Simulation Program-FORTRAN (HSPF) is a powerful time variable hydrologic model that has rarely been applied in arid environments. Here, the performance of HSPF in southern California was assessed, testing its ability to predict annual volume, daily average flow, and hourly flow. The model was parameterized with eight land use categories and physical watershed characteristics. It was calibrated using rainfall and measured flow over a five-year period in a predominantly undeveloped watershed and it was validated using a subsequent 4-year period. The process was repeated in a separate, predominantly urbanized watershed over the same time span. Annual volume predictions correlated well with measured flow in both the undeveloped and developed watersheds. Daily flow predictions correlated well with measured flow following rain events, but predictions were poor during extended dry weather periods in the developed watershed. This modeling difficulty during dry-weather periods reflects the large influence of, and the poor accounting in the model for, artificially introduced water from human activities, such as landscape overwatering, that can be important sources of water in urbanized arid environments. Hourly flow predictions mistimed peak flows, reflecting spatial and temporal heterogeneity of rainfall within the watershed. Model correlation increased considerably when predictions were averaged over longer time periods, reaching an asymptote after an 11-hour averaging window.
(KEY TERMS: HSPF; hydrology; urban; watershed; model; California.)

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INTRODUCTION

Watershed models are widely applied to investigate runoff dynamics and associated pollutant loadings. HSPF (Bicknell *et al.,* 1997) is one of the most popular of these models, having been applied to simulate runoff in areas ranging from small agricultural watersheds in Iowa (Donigian *et al.,* 1983) to large multiuse watersheds in the Potomac River Basin (Stigall *et al.,* 1984). It is a flexible model that has been used to address a wide variety of management issues (Moore et al., 1992), including urbanization related changes in stream flow (Ng and Marsalek, 1989; Brun and Band, 2000) and sediment transport (Chew *et al.,* 1991).

HSPF has been applied extensively in watersheds with perennial stream flow, but it has had only limited application in arid areas. Arid environments present several modeling challenges, as flow is severely diminished in the dry season and even between storms. Flow in arid systems also changes rapidly, sometimes from near zero to annual peak flows in an hour and receding to base flow again within a day (Tiefenthaler *et al.,* 2001). Arid systems also typically have large volumes of imported water, which are not as easily accounted for as rainfall and ground water inputs.

Modeling challenges are even greater in urban arid areas. The impervious surface characteristic of urban environments exacerbates the episodic flow. In addition, water quality management applications in urban environments often target only a small portion of a storm event, such as capturing or treating the first centimeter of rainfall, and therefore require modeling on time scales as short as an hour. Most HSPF applications to date, even in ground water-driven continuously flowing streams, are typically conducted on daily or annual time scales.

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Of the few arid HSPF applications (Rahman and Salbe, 1995; Guay, 2002; Berris *et al.,* 2001), none have focused on urban environments and only attempted simulations on daily time scales. Here HSPF's predictive ability is evaluated on three time scales (hourly, daily, and annual) in two arid southern California watersheds: one urban and one that is largely undeveloped.

METHODS

Study Area Description

The two watersheds studied were the Malibu and Ballona Creek watersheds, both of which drain to Santa Monica Bay (SMB), California (Figure 1). The Malibu Creek watershed is largely undeveloped with only 4 percent impervious surface (Dojiri *et al.,* 2003). The watershed (286 km^2) contains six subbasins (State of California, 1997), has significant elevation changes (918 m) and an average watershed slope of 18 percent. There are three small dam created lakes in the watershed and a small (0.4 m^3/s) wastewater treatment plant that discharges above the stream gages.

In contrast, the Ballona Creek watershed drains urban Los Angeles and is almost 90 percent developed (Dojiri *et al.,* 2003). The Ballona Creek watershed (338 km^2) contains seven subbasins (LACDPW, 1999) and is relatively flat, with a maximum average slope of 6 percent. Ballona Creek has no dams or treatment plant discharges.

An average of 20 storms and 34 cm of precipitation per year are measured at the Los Angeles International Airport (Ackerman and Weisberg, 2003), which is located near the mouth of the Ballona watershed. Rainfall spatial heterogeneity is highly pronounced in the Malibu Creek watershed, where average annual rainfall ranges from 34 to 79 cm among subwatersheds, resulting from elevation induced orographic differences (Daly *et al.,* 1994). Average rainfall among subwatersheds in the flatter Ballona Creek watershed ranges only between 34 and 53 cm. Seventy percent of annual rainfall occurs between January and March, with virtually no rain from May through October

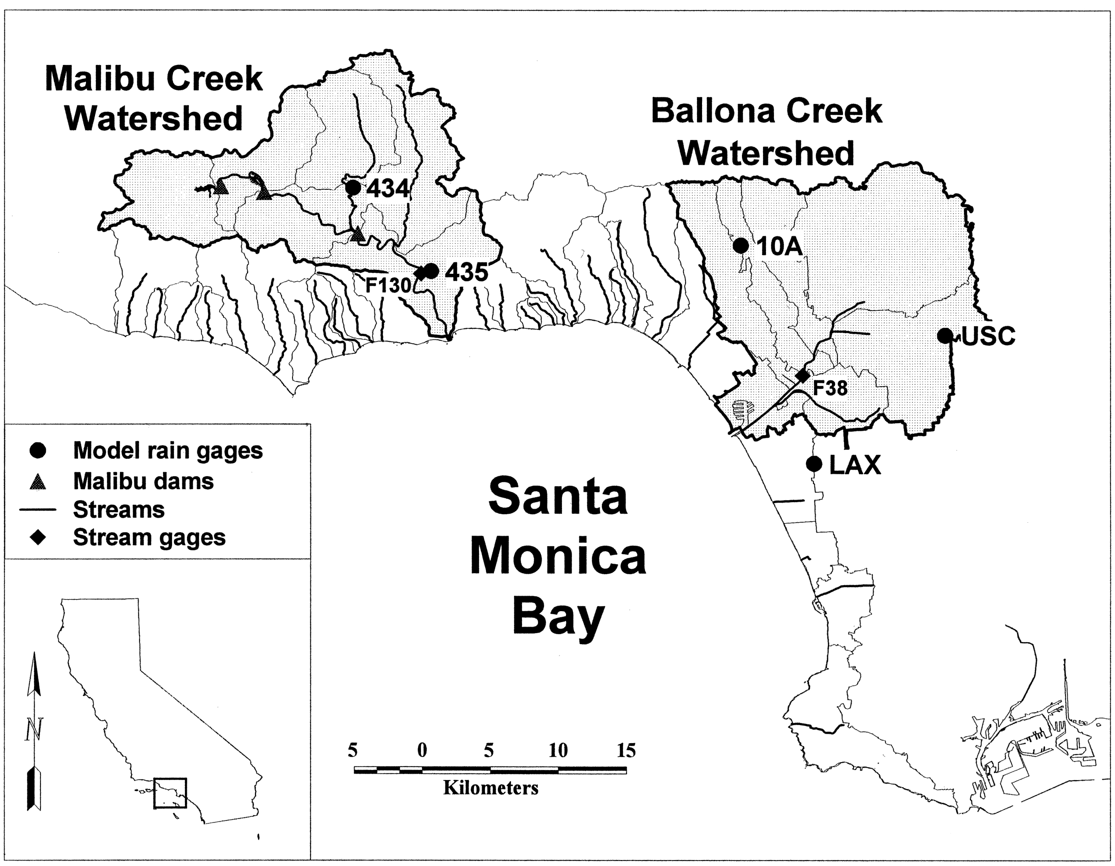


Figure 1. Location of Rain and Stream Gages, Watershed Delineations, Streams and Significant Dams in the Malibu Creek and Ballona Creek Watersheds.

(Ackerman and Weisberg, 2003). Soils in both watersheds have slow (Class C) to very slow (Class D) infiltration rates (USDA, 1994).

Data Sources

HSPF predicts flow based on rainfall, land use characteristics, and stream geometry. Meteorological data (water years 1988 to 1998) were obtained from the Los Angeles International Airport (LAX) station (NCDC, 2001; USEPA, 2002). The simulation period included extreme (El Niño and La Niña) rainfall years, as well as a median year. Rainfall data for the Malibu watershed were obtained from Los Angeles County Department of Public Works (LACDPW) Gages 434 and 435 (Figure 1). Rainfall data for the Ballona Creek watershed were obtained from LACDPW Gage 10A and from the LAX station. All gages measure rainfall in 0.254 mm increments. Rainfall in unmonitored subwatersheds was estimated from the nearest gage, after adjustment for orographic differences using topography modeled annual rainfall (PRISM) (Daly and Taylor, 1998). On a few occasions, data from the gages in the watershed were unavailable due to gage malfunctions; in these instances, rainfall data from a nearby watershed, after adjustment with the PRISM model, were used.

Daily potential evapotranspiration was calculated from measured meteorological data at LAX. Daily maximum and minimum temperatures were used by the WDM Utility (Hummel *et al.,* 2001) to calculate potential evapotranspiration based on the Jensen and Haise (1963) formula. Actual evapotranspiration is calculated internally within HSPF as a function of soil moisture storages and the evapotranspiration potential.

Detailed land use data were obtained from the Southern California Association of Governments and aggregated into eight land use categories based on like activities. Minimum land use resolution was 8 m^2. The percent of perviousness for each land use (Table 1) was established following LACDPW methods (DePoto *et al.,* 1991).

The LACDPW Gages F130 and F38C were used for stream flow data in Malibu and Ballona Creeks, respectively. Malibu Creek stream network and cross sections were defined using information from the U.S. Environmental Protection Agency (USEPA) BASINS RF3 files (USEPA, 1998) and U.S. Geological Survey (USGS) quadrangle maps. Streams in the Ballona Creek watershed are concrete lined trapezoidal or rectangular channels, and cross sections were defined using as-built drawings (LACDPW, 1999).

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

Model Application

The Malibu Creek model was initialized by simulating water year (WY) 1988, calibrated using WY 1989 to 1994, and validated using WY 1995 to 1998 from the most downstream LACDPW gage. The gage was 7 km from the mouth of the watershed and captured runoff from 272 km^2, or roughly 52 percent of the watershed, along with discharge from the Tapia wastewater treatment plant. Of the three Malibu Creek watershed dams, only the most downstream dam had flow rating information. Ratings for the other two dams were extrapolated from the rated dam. Model calibration was performed by universally adjusting model parameters (Table 2) across land use types using the HSP Expert System and calibrating the results to measured flow data. The HSP Expert System consists of a set of hierarchical rules designed to guide the calibration of the model through a systematic evaluation of model parameters by evaluating water balance, low flow, storm flow, and seasonal adjustments (Lumb *et al.,* 1994). Modeled monthly and annual volumes were evaluated according to criteria defined by Donigian (2002).

The Ballona Creek model was applied using the same methodology as in Malibu Creek over the same time period. Its most downstream flow gage was upstream of the tidal prism, 6 km from the coast, and captured runoff from 230 km^2, or roughly 44 percent of the watershed. Urban nonpoint source flows from human activities (lawn overwatering, car washing, etc.) were represented by assigning a base flow of 0.4 m^3/s based on historic average dry weather flow during the summer months of June through August.

Model predictions were evaluated by comparing them to measured flows at three time scales: annual volume, daily average flow, and hourly flow. To further assess model accuracy, daily flow predictions were also evaluated separately under dry weather and wet weather conditions. Wet weather conditions

TABLE 2. Model Parameters Utilized for Modeling of Santa Monica Bay.

		Value	Units
Pervious Parameters			
Fraction of Remaining E-T From Active Ground Water Storage	AGEWTP	0.05	None
Basic Ground Water Recession Rate	AGWRC	0.92	1/d
Fraction of Remaining E-T From Base Flow	BASETP	0.05	None
Interception Storage Capacity	CEPSC	0.25	cm
Fraction of Ground Water to Deep Aquifer	DEEPFR	0.40	None
Forest Fraction	FOREST	0.0	Percent
Infiltration Equation Exponent	INFEXP	2.0	None
Ratio Between the Maximum and Mean Infiltration Capacities	INFILD	2.0	None
Infiltration Capacity	INFILT	0.10	cm/hr
Interflow Inflow Parameter	INTFW	1.50	None
Interflow Recession Parameter	IRC	0.70	1/d
Ground Water Recession Flow Coefficient	KVARY	7.6	1/cm
Overland Flow Length	LSUR	61	m
Lower Zone E-T Parameter	LZETP	0.70	None
Lower Zone Nominal Storage	LZSN	25	cm
Manning's n for Overland Flow	NSUR	0.20	none
Temperature Maximum for Evapotranspiration (E-T)	PETMAX	1.7	˚C
Temperature That E-T is Zero	PETMIN	-1.1	˚C
Overland Flow Slope	SLSUR	0.03	none
Upper Zone Nominal Storage	UZSN	3.0	cm
Impervious Parameters			
Overland Flow Length	LSUR	61	m
Manning's n for Overland Flow	NSUR	0.025	none
Temperature Maximum for E-T	PETMAX	1.7	˚C
Temperature That E-T is Zero	PETMIN	-1.1	˚C
Retention Storage Capacity of the Surface	RETSC	0.18	cm
Slope	SLSUR	0.030	None

were defined as days when flow was more than 20 percent above prestorm flows.

RESULTS

Malibu Creek

Modeled monthly and annual volumes correlated well (Figure 2). The slope of the relationship between measured and predicted volume was nearly unity (0.99).

On daily time scales, the model calibrated well when flow was elevated due to rainfall. Following storms, daily average flow during the calibration period ranged from 1 to 69 m^3/s and the model predicted 83 percent of this variability (Figure 3); the model validated equally well with flows of 1 to 143 m^3/s, with 86 percent of the variability predicted. In contrast, there was a poor correlation between predicted and measured flow during dry weather (Table 3). When average daily flow was less than 1 m^3/s, there was no relationship in either the calibration or validation periods. Average daily flow less than 1 m^3/s occurred on 79 percent of the days, but comprised only 18 percent of the total volume.

Ballona Creek

The model predictions correlated well with measured monthly and annual runoff volume in Ballona Creek (Figure 2). The slope of the relationship between modeled and measured volumes was near unity (1.14). Most of the differences from unity were attributable to a small number of very large (> 250 mm/day) rain events in a single El Niño year (1998).

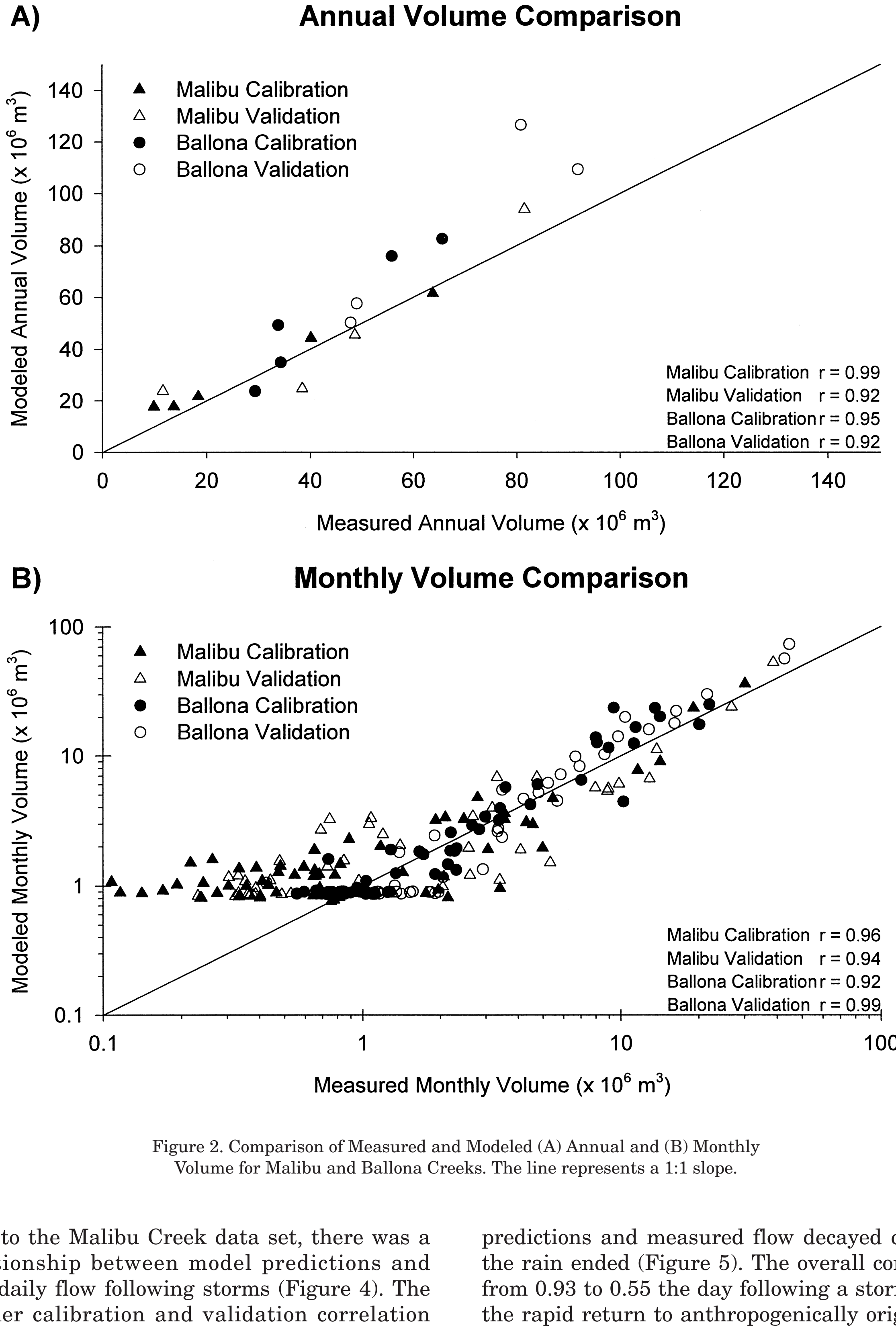
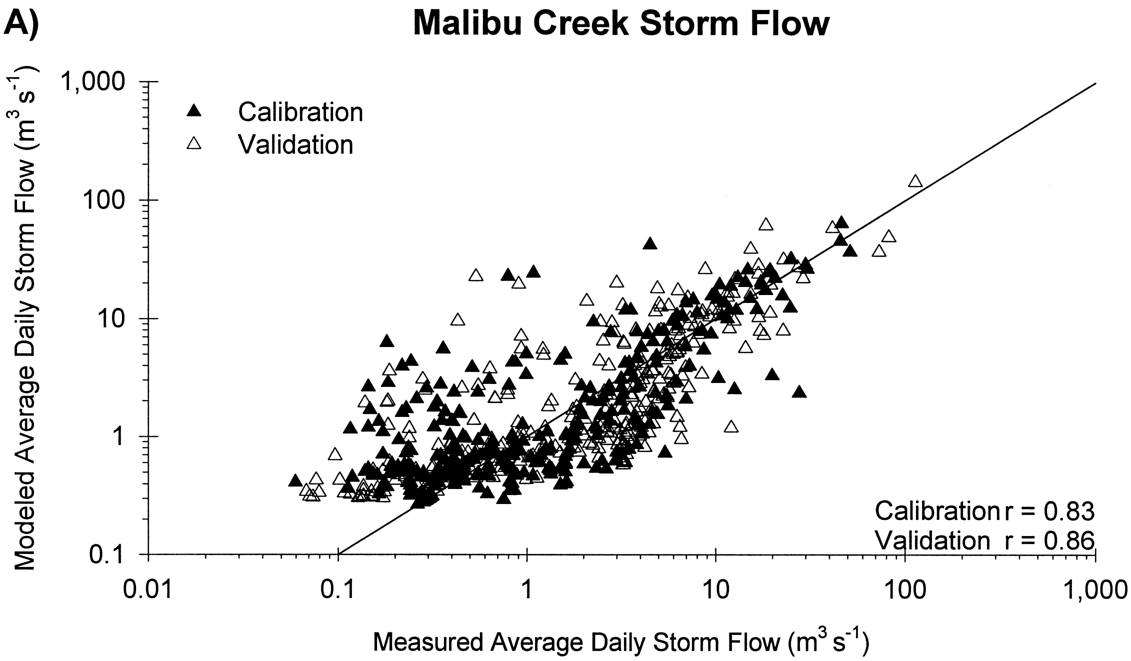


Figure 2. Comparison of Measured and Modeled (A) Annual and (B) Monthly Volume for Malibu and Ballona Creeks. The line represents a 1:1 slope.

Similar to the Malibu Creek data set, there was a good relationship between model predictions and measured daily flow following storms (Figure 4). The wet weather calibration and validation correlation between predicted and actual daily flow was 0.81 and 0.94, respectively. The relationship was statistically insignificant during dry weather (Table 3). Unlike Malibu Creek, the relationship between modeled predictions and measured flow decayed quickly after the rain ended (Figure 5). The overall correlation fell from 0.93 to 0.55 the day following a storm, reflecting the rapid return to anthropogenically originated base flow conditions in this highly impervious watershed.

The accuracy of daily flow predictions improved with increasing storm size (Figure 6). Prediction accuracy was poor for storms smaller than 10 mm. Errors



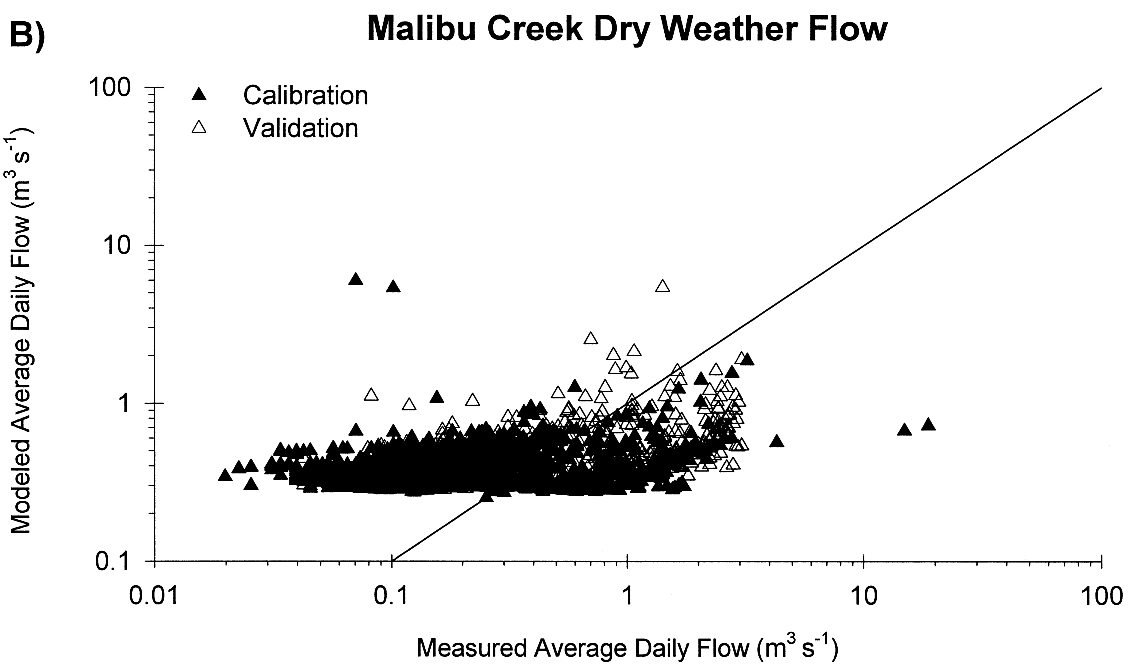


Figure 3. Comparison of Modeled and Measured (A) Wet Weather and (B) Dry Weather Flows on Malibu Creek.

for these small events routinely exceeded 200 percent and were positively skewed. In contrast, modeled estimates for storms greater than 10 mm typically were within a factor of two of measured daily average flow.

The model was ineffective at predicting hourly flow rate with a correlation between modeled and measured values of 0.65. This relationship improved when a larger averaging window was used (Figure 7). Correlation coefficients improved asymptotically, reaching 0.86 when the averaging window was 11 hours.

DISCUSSION

The results from this study demonstrate that the hydrodynamic component of HSPF can be applied successfully in arid environments, particularly if results are interpreted on monthly or annual time scales. The model also performed well for predicting daily flow during wet weather periods in both undeveloped and urbanized watersheds. The correlations

TABLE 3. Summary of Calibration and Validation Statistics for Malibu Creek and Ballona Creek.

Year		Correlation Coefficient	Average Error	RMSE	Coefficient of Efficiency	Modeling Efficiency
			Malibu Creek			
1989 to 1994	Storm	0.83	-0.4	4.2	0.60	-0.27
	Dry	0.14	-0.1	0.8	-0.02	0.90
1995 to 1998	Storm	0.86	-0.3	5.7	0.66	-0.26
	Dry	0.42	0.1	0.6	0.17	0.83
			Ballona Creek			
1989 to 1994	Storm	0.86	-2.1	9.6	0.63	-0.39
	Dry	0.29	-0.01	0.3	-1.86	-1.86
1995 to 1998	Storm	0.97	-4.0	9.0	0.78	-0.81
	Dry	0.40	0.08	0.7	-3.79	-3.79

where

$$Correlation\ Coefficient = \frac{\sum\left(O-\bar{O}\right)\left(P-\bar{P}\right)}{\sqrt{\sum\left(O-\bar{O}\right)^2\left(P-\bar{P}\right)^2}} \qquad Average\ Error = \frac{\sum(O-P)}{n}$$

$$Modeling\ Efficiency = \frac{\sum\left(O-\bar{O}\right)^2 - \sum\left(P-\bar{O}\right)^2}{\sum\left(O-\bar{O}\right)^2} \qquad RMSE = \sqrt{\frac{\sum(O-P)^2}{n}}$$

$$Coefficient\ of\ Efficiency = 1 - \frac{\sum(P-O)^2}{\sum\left(O-\bar{O}\right)^2}$$

between modeled and measured flow were higher than typically observed in temperate applications of HSPF (Brun and Band, 2000). Urban watersheds often have well engineered storm water conveyance systems to reduce flooding, and the southern Santa Monica Bay watersheds are among the most engineered in the world (Brownlie and Taylor, 1981). These pipe or concrete lined conveyance systems are more easily modeled than natural systems with uneven bottoms, spatially-variable friction coefficients, and ground water interactions.

The model worked poorly under dry weather conditions, which probably reflects the large contribution of nonstorm related flows that are added to the system. For example, the Metropolitan Water District of Southern California imports more than 680 x 10^6 m^3 of water annually from northern California and the Colorado River (MWD, 2002) for domestic and commercial use. Most of the stream flow during southern California's dry season is the result of dry-weather runoff that finds its way into the storm drain systems from activities such as lawn overwatering and car washing. These contributions from out-of-basin sources, which are not well quantified, are temporally variable and are not easily accounted for in the model. They represent a challenge in applying any hydrologic model in an arid, urban environment.

The effect of dry weather runoff in the arid environment was exacerbated in heavily urbanized Ballona Creek, where the model did not work effectively just two days following storms. The highly impervious watershed is characterized by steep, short hydrographs (Leecaster *et al.,* 2002), which resulted in a quick return to a dry weather flow dominated system. This contrasts with the less developed Malibu Creek watershed, in which the extended storm hydrographs resulting from subsurface flows showed good correlation for more than a week after a storm (Figure 5). Subsurface flows in Malibu Creek were more than three times the percentage of total flow in Ballona Creek, reflecting the larger percentage of pervious surfaces.

The model also had difficulty estimating flow during small (< 10 mm) storm events (Figure 6). The problem with small storms appears to be spatial heterogeneity in rainfall and the inability to resolve localized storm cells in the highly impervious watersheds.

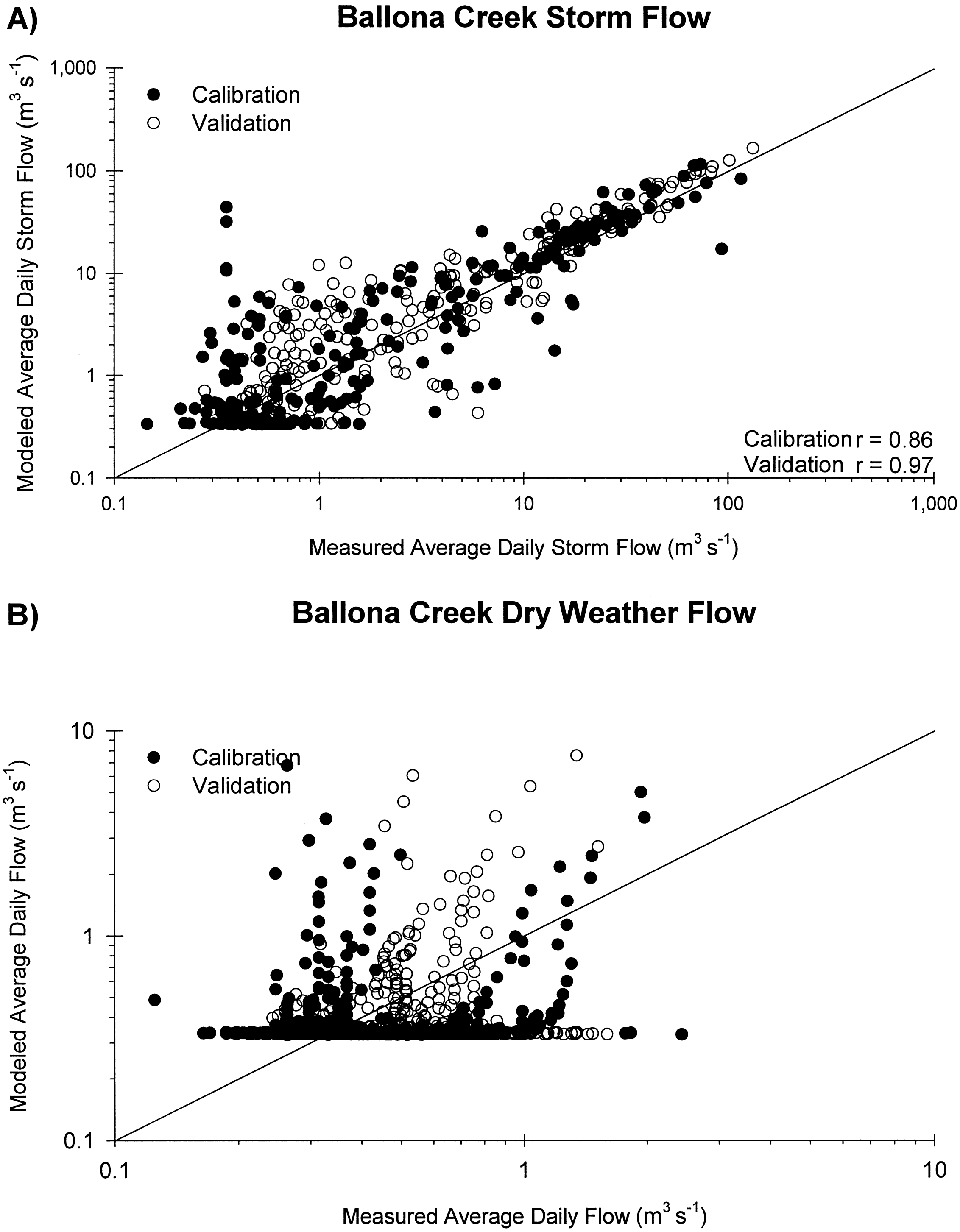


Figure 4. Comparison of Modeled and Measured (A) Wet Weather and (B) Dry Weather Flows on Ballona Creek.

The modeled watersheds each had two rain gages, which are more than are typically found in watersheds of this size, but that appears to be inadequate because rainfall does not occur watershed wide for most storms smaller than 10 mm (Ackerman and Weisberg, 2003). Krejcik *et al.* (1998) detailed the need for high density rain gage networks to accurately describe rainfall in an urban basin in the Czech Republic when investigating runoff associated with individual storms. Fo *et al.* (1999) also found that better representation of watershed rainfall had the greatest impact on model accuracy.

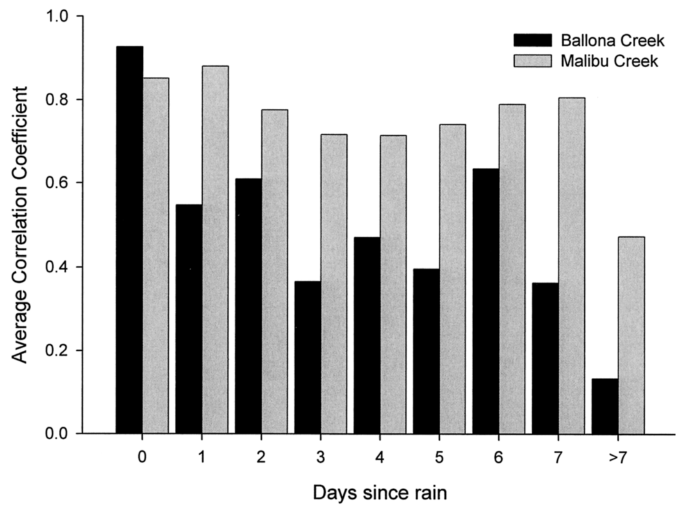


Figure 5. Correlation Coefficient Between Measured and Modeled Average Daily Flows on Malibu and Ballona Creeks as a Function of Days Since Rain.

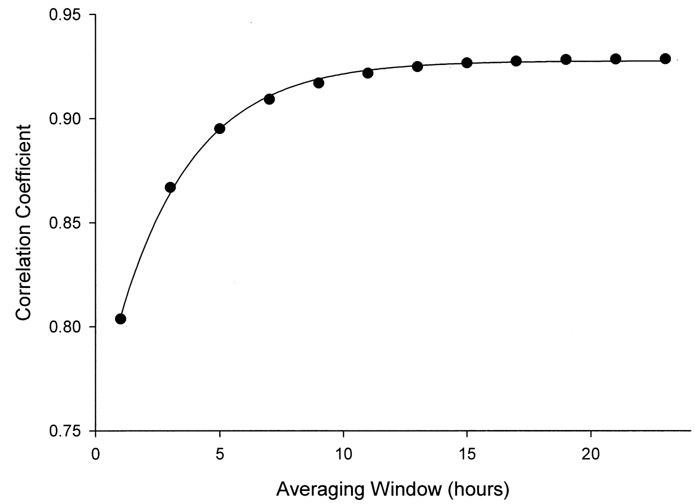


Figure 7. Correlation Coefficient of Measured Versus Modeled Flow on Ballona Creek as a Function of Increasing Hourly Averaging Windows During Wet Weather Flows.

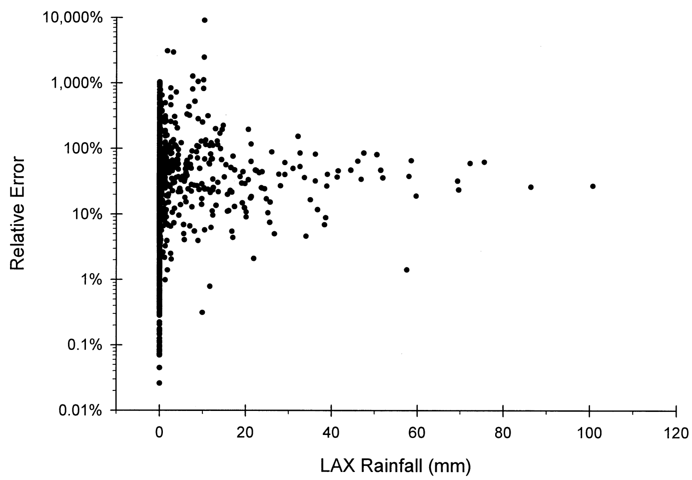


Figure 6. Modeled Error in Average Daily Flows on Ballona Creek as a Function of Rainfall.

The model also had limited effectiveness when applied to hourly time scales. Rainfall spatial heterogeneity may contribute to this, though temporal heterogeneity is probably more important than spatial heterogeneity for short time scale predictions. Because the watersheds examined in this study were larger than 250 km^2, the initiation of rainfall can vary by several hours at different locations as the storm moves through the basin. Without a larger number of rain gages or more detailed spatial rainfall information (e.g., hourly radar estimates), averaging over nearly 11 hours was necessary to overcome this heterogeneity and achieve optimum model output.

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