Evaluating HSPF in an arid, urbanized watershed

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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, we assess the performance of HSPF in southern California, testing its ability to predict annual volume, daily average flow, and hourly flow. The model was parameterized with 13 land use categories and physical watershed characteristics. It was calibrated using rainfall and measured flow over a 10-year period in a predominantly undeveloped watershed; and it was validated using flow data from a separate, predominantly urbanized watershed over the same time span. Annual volume predictions correlated well with measured flow in both the calibration (r = 0.94) and validation (r = 0.89) watersheds. Daily flow predictions correlated well with measured flow following rain events, but predictions were poor during extended dry-weather periods. 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 lawn overwatering or car washing that can be important water sources of contaminants in arid environments. Hourly flow predictions mis-timed peak flows, reflecting spatial and temporal heterogeneity of rainfall within the watershed. Model performance increased considerably when predictions were averaged over longer time periods, reaching an asymptote after an 11-h averaging window.

INTRODUCTION

Watershed models are widely applied to investigate runoff dynamics and associated pollutant loadings. The Hydrological Simulation Program – Fortran (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 multi-use 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).

Although HSPF has been applied extensively in watersheds with perennial stream flows, it has had only limited application in arid areas, where rainfall is minimal and streams can run nearly dry between storm events. The hydrology of the Truckee River basin, which spans a part of the California-Nevada border, was simulated by Berris *et al.* (2001). Rahman and Salbe (1995) used it to model nutrient dynamics in the Hawkesbury River. The HSPF was also used to simulate two arid watersheds in South Africa (Johanson 1989). In all of these studies, though, the watersheds were predominantly undeveloped or agricultural.

This study focused on calibrating, validating, and evaluating HSPF in two arid watersheds within Santa Monica Bay (SMB), California, where there is an average of only 20 storms and 34 cm of precipitation per year. Seventy percent of annual rainfall occurs between January and March, with virtually no rain from May through October (Ackerman and Weisberg 2003). The SMB was selected because it has a dichotomy of watershed types that allows the testing of HSPF's capabilities under different land use conditions. The northern SMB watersheds are largely undeveloped preserves, while watersheds to the south drain urban Los Angeles and are almost 90% developed (Dojiri *et al.* in press).

METHODS

The model was calibrated in the largely undeveloped Malibu Creek watershed and then validated in the highly developed Ballona Creek watershed (Figure 1). 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 were defined as days when flow was more than 20% above pre-storm flows.

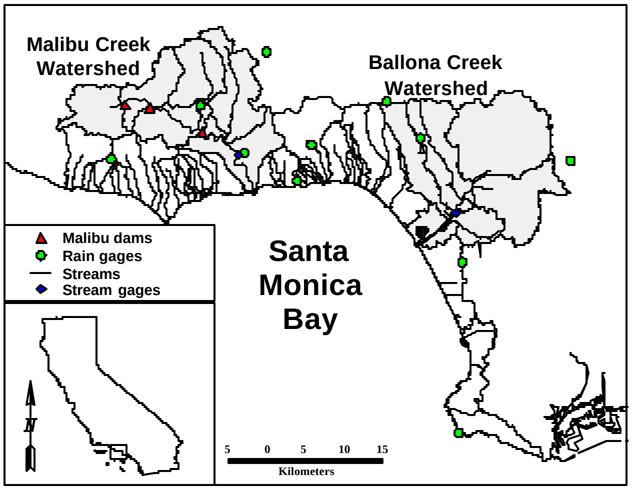

Figure 1. Location of rain and stream gages, watershed delineations, streams, and significant dams in the calibration and validation watersheds.

Data Sources

The HSPF predicts flow based on rainfall, land use characteristics, and stream geometry. Meteorological data for the calibration watershed were obtained from the Los Angeles International Airport (LAX) (NCDC 2001, U.S. EPA 2002) station. 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 sub-watersheds 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.

Detailed land use data were obtained from the Southern California Association of Governments and aggregated from 44 to 13 land use categories (Table 1). Minimum land use resolution was 8 m^2. The Malibu Creek and Ballona Creek watersheds were delineated by combining data from the California Department of Fish and Game (1998) and the LACDPW. The percent of imperviousness for each land use (Table 1) was established following Escobar (1999).

The LACDPW Gages F130 and F38C were used for stream flow data in Malibu and Ballona creeks, respectively. Stream network connectivity was obtained from LACDPW engineering drawings. Malibu Creek stream cross-sections were defined using United States Geological Survey (USGS) quadrangle maps. Streams in the Ballona Creek watershed are concrete-lined trapezoidal or rectangular channels, and cross-sections were defined using the as-built drawings.

Calibration and Validation

The model was calibrated using flow data for water years 1989-1998 from the most downstream LACDPW gage in the Malibu Creek watershed. The gage captured runoff from 272 km^2, or roughly 52% of the watershed. 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 (Lumb *et al.* 1994) and calibrating the results to measured flow data.

The model was validated in the Ballona Creek watershed using daily flow data for water years 1989-1998. The most downstream flow gage captured runoff from 230 km^2, or roughly 44% of the watershed. All of the modeled parameters calibrated in Malibu Creek were universally applied to Ballona Creek, except that imported source flows from human activities such as lawn overwatering were present in Ballona Creek and were assigned 0.4 m^{3}s^{-1} based on historic average dry-weather flow during the summer months of June through August.

RESULTS

Calibration

Modeled annual volumes correlated well (r = 0.94) with measured volumes in Malibu Creek (Figure 2). The slope of the relationship between measured and predicted volume was nearly unity (0.99).

The model worked well on daily time scales when flow was elevated due to rainfall. Following storms, daily average flow ranged from 1-135 m^{3}s^{-1} and the model predicted 85% of this variability (Figure 3). In contrast, there was a poor correlation between predicted and measured flow during dry weather. When average daily flow was less than 1 m^{3}s^{-1}, there was no relationship. Average daily flow less than 1 m^{3}s^{-1} occurred on 79% of the days in our calibration period, but comprised only 18% of the total volume.

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

Original Land Use	Aggregated Land Use	Percent Pervious
Agriculture	Agriculture	94
Commercial	Commercial	15
Communication Facilities	Industrial	25
Education	Commercial	15
Extraction	Industrial	25
Floodways and Structures	Water	100
General Office	Commercial	15
Golf Courses	Open	97
Heavy Industrial	Industrial	25
High-Density Single-Family Residential	High-Density Residential	40
Industrial	Industrial	25
Institutional	Commercial	15
Light Industrial	Industrial	25
Light Industrial/Mixed Residential	Mixed Urban	50
Low-Density Residential	Low-Density Residential	60
Low-Density Single-Family Residential	Low-Density Residential	60
Maintenance Yards	Industrial	25
Marina Facilities	Industrial	25
Medium- to High-Density Residential	High-Density Residential	40
Military Installations	Industrial	25
Mixed Commercial and Industrial	Mixed Urban	50
Mixed Residential	Mixed Urban	50
Mixed Transportation and Utility	Industrial	25
Mixed Urban	Mixed Urban	50
Mobile Homes and Trailer Parks	High-Density Residential	40
Multiple Family Residential	High-Density Residential	40
Natural Resources Extraction	Industrial	25
Nurseries and Vineyards	Agriculture	94
Open Space & Recreation	Open	97
Other Commercial	Commercial	15
Public Facilities & Institutions	Commercial	15
Receiving Waters	Water	100
Retail/Commercial	Commercial	15
Rural-Density Residential	Low-Density Residential	60
Rural Residential	Low-Density Residential	60
Transportation	Industrial	25
Transportation & Utilities	Industrial	25
Under Construction	Open	97
Urban Vacant	Open	97
Utility Facilities	Industrial	25
Vacant	Open	97
Water & Floodways	Water	100

Validation

The model predictions correlated well (r = 0.89) with measured 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).

Similar to the calibration data set, there was a good relationship between model predictions and measured daily flow following storms (Figure 4). The correlation between predicted and actual daily flow was 0.89 during wet weather, but the relationship was statistically insignificant during dry weather. Unlike Malibu Creek, the relationship between modeled predictions and measured flow decayed quickly after

Table 2. Model parameters utilized for modeling of Santa Monica Bay.

Pervious Parameters		**Value**	**Units**
Fraction of Remaining E-T from Active Groundwater Storage	AGEWTP	0.05	None
Basic Groundwater Recession Rate	AGWRC	0.92	1/d
Fraction of Remaining E-T from Baseflow	BASETP	0.05	None
Interception Storage Capacity	CEPSC	0.25	cm
Fraction of Groundwater to Deep Aquifer	DEEPFR	0.40	None
Forest Fraction	FOREST	0.0	%
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
Groundwater 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	Complex
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		**Value**	**Units**
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

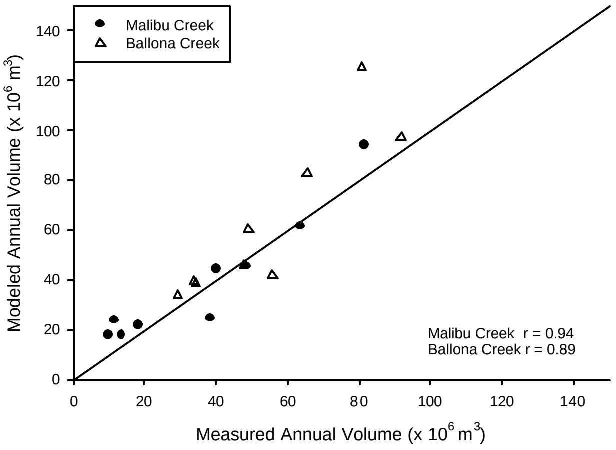

Figure 2. Comparison of measured and modeled annual volume for Malibu and Ballona creeks between 1989 and 1998.

the rain ended (Figure 5). The correlation fell to 0.47 the day following a storm, reflecting the rapid return to 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 for these small events routinely exceeded 200% 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 less than 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 h.

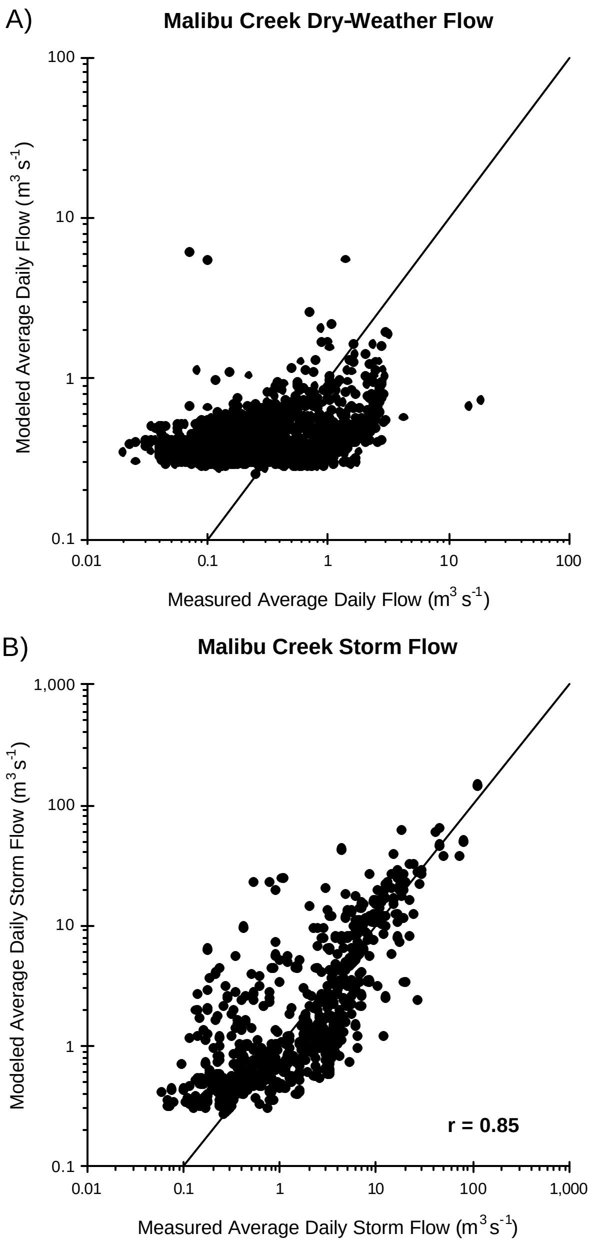

Figure 3. Comparison of modeled and measured dry-weather (A) and wet-weather (B) flows on Malibu Creek.

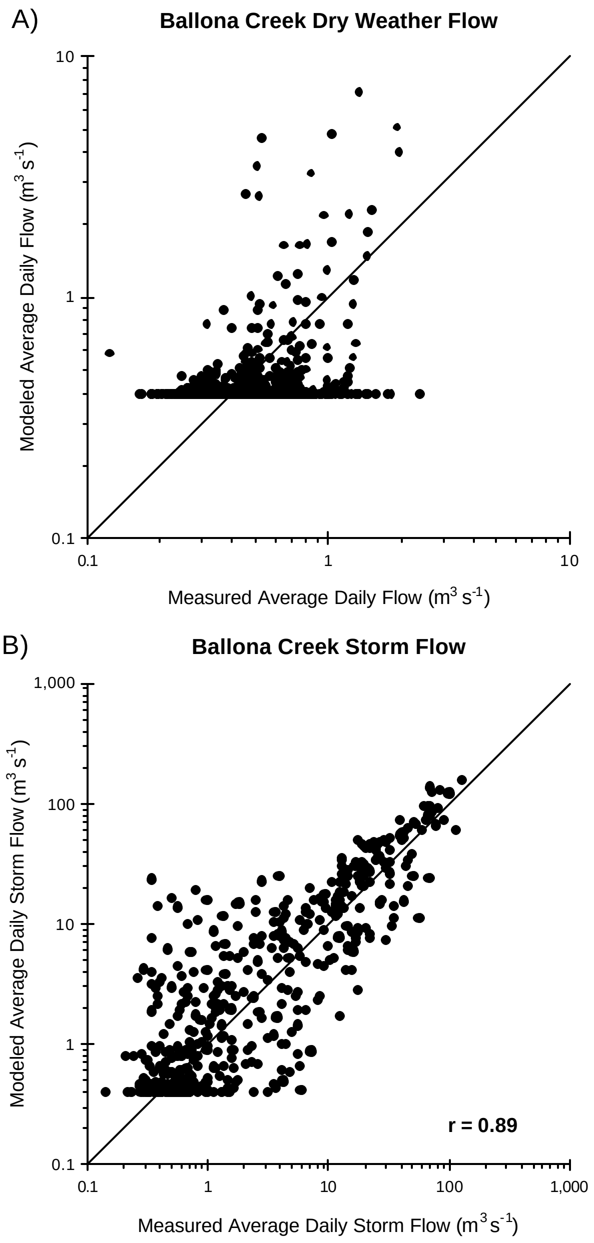

Figure 4. Comparison of modeled and measured dry-weather (A) and wet-weather (B) flows on Ballona Creek.

DISCUSSION

The results from this study demonstrate that the hydrodynamic component of HSPF can be applied successfully in arid environments, particularly if used on annual time scales. The model also performed well for predicting daily flow during wet-weather periods. Our correlation of 0.89 between modeled and measured flow in our validation watershed is higher than typically observed in temperate applications of HSPF (Brun and Band 2000). This may reflect that our application was in a highly impervious urban environment. Urban watersheds often have well-engineered stormwater 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 groundwater interactions.

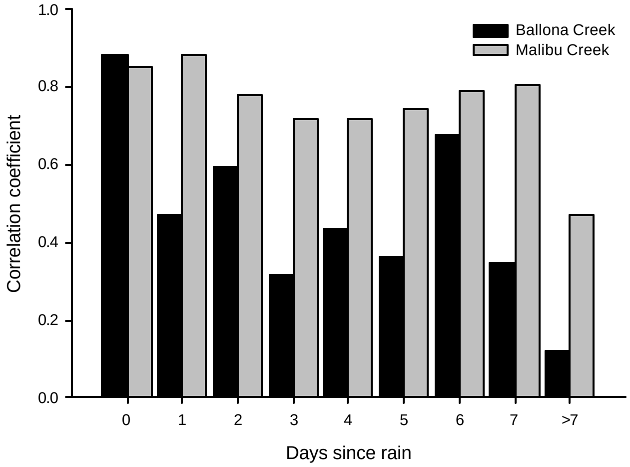

Figure 5. Correlation coefficient between measured and modeled average daily flows on Malibu and Ballona creeks as a function of days since rain.

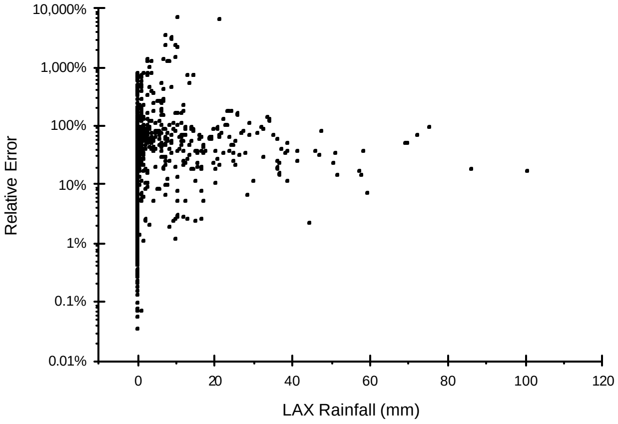

Figure 6. Modeled error in average daily flows on Ballona Creek as a function of rainfall.

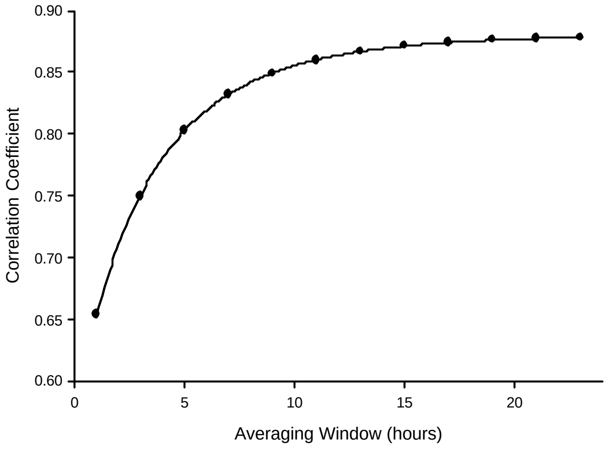

Figure 7. Correlation coefficient of measured versus modeled flow on Ballona Creek as a function of increasing hourly averaging windows during wet-weather flows.

The model worked poorly under dry-weather conditions, which probably reflects the large contribution of non-storm-related flows that are added to the system. 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). 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).

The model also had difficulty estimating flow during small (< 10 mm) storm events. 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. The modeled watersheds each had two rain gages, which is more than are typically found in watersheds of this size, but even that appears to be inadequate because rainfall does not occur watershed-wide for most storms smaller than 10 mm (Ackerman and Weisberg 2003). Rainfall spatial heterogeneity is highly pronounced in the Malibu Creek watershed, where there is more than a three-fold difference in annual rain among sub-watersheds, resulting from orographic differences induced by elevation (Daly *et al.* 1994).

The model was also limited when applied to short (i.e., hourly) time scales. This also reflects rainfall heterogeneity, although temporal heterogeneity was probably more important than spatial heterogeneity for short time-scale predictions. Because the watershed is large, 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 h was necessary to overcome this heterogeneity and achieve optimum model output.

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