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DRY AND WET WEATHER FLOW NUTRIENT LOADS FROM A LOS ANGELES WATERSHED[1]

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ABSTRACT: Effective watershed management requires an accurate assessment of the pollutant loads from the associated point and nonpoint sources. The importance of wet weather flow (WWF) pollutant loads is well known, but in semi-arid regions where urbanization is significant the pollutant load in dry weather flow (DWF) may also be important. This research compares the relative contributions of potential contaminants discharged in DWF and WWF from the Ballona Creek Watershed in Los Angeles, California. Models to predict DWF and WWF loads of total suspended solids, biochemical oxygen demand, nitrate-nitrogen, nitrite-nitrogen, ammonia-nitrogen, total Kjeldahl nitrogen, and total phosphorus from the Ballona Creek Watershed for six water years dating from 1991 to 1996 were developed. The contaminants studied were selected based on data availability and their potential importance in the degradation of Ballona Creek and Santa Monica Bay beneficial uses. Wet weather flow was found to contribute approximately 75 percent to 90 percent of the total annual flow volume discharged by the Ballona Creek Watershed. Pollutant loads are also predominantly due to WWF, but during the dry season, DWF is a more significant contributor. Wet weather flow accounts for 67 to 98 percent of the annual load of the constituents studied. During the dry season, however, the portion attributable to DWF increases to greater than 40 percent for all constituents except biochemical oxygen demand and total suspended solids. When individual catchments within the watershed are considered, the DWF pollutant load from the largest catchment is similar to the WWF pollutant load in two other major catchments. This research indicates WWF is the most significant source of nonpoint source pollution load on an annual basis, but management of the effects of the nonpoint source pollutant load should consider the seasonal importance of DWF.
(KEY TERMS: nonpoint source pollution; watershed management; urban runoff; dry weather flow; wet weather flow; storm water modeling; water quality.)

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INTRODUCTION

The watershed management approach is being promoted by federal agencies and implemented increasingly in many regions of the United States (USEPA, 1997a). The underlying goal of the watershed approach is to restore aquatic ecosystems and protect human health, which is often represented as the prohibition of exceedances of water quality criteria in receiving waters (USEPA, 1997b). Contaminant concentrations attained in receiving waters are a function of the waterbody characteristics and the spatial and temporal distribution of the pollutant loads. Pollutant sources are generally categorized as point sources (i.e., steady discharges at a known location, or nonpoint sources; highly variable discharges in both space and time; and urban runoff) (Novotny, 1999). Accurate definition of the spatial and temporal distribution of point and nonpoint pollutant sources is a critical initial step in watershed management.

Urban wet weather flow (WWF) discharges to receiving waters have long been recognized as significant sources of pollutants and causes of water quality

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degradation (APWA, 1969; Field and Turkeltaub, 1981; Heaney and Huber, 1984). For example, in the 1996 U.S. Environmental Protection Agency (USEPA) National Water Quality Inventory, urban runoff and storm sewer discharges were listed as the primary cause of impairment of 5 percent of the river miles surveyed, 8 percent of the lake area surveyed, 18 percent of the estuaries surveyed, and 7 percent of the wetlands surveyed (USEPA, 1998). By design, municipal separate storm sewers should have zero discharge during dry weather. However, during dry weather conditions, storm drains or streams modified structurally into storm drains may convey considerable amounts of National Pollutant Discharge Elimination System (NPDES) permitted discharges, incidental nuisance flows and inappropriate discharges. In Los Angeles, for example, DWF from storm drains is comprised mostly of nuisance flows and NPDES permitted discharges having high concentrations of potential pollutants (Lau *et al.,* 1994). The low flow rates associated with DWF mask the potential water quality threat it represents compared to the enormous flow rates and pulse pollutant loads representative of WWF discharges.

In this study, the relative long term pollutant load from DWF and WWF discharged from the Ballona Creek Watershed, a large urban watershed located in Los Angeles, California, is quantified. In Los Angeles, historical streams and rivers have been modified into storm drains for flood control purposes. These massive concrete channels convey flow throughout the year, even though Los Angeles rarely has significant rainfall/runoff during the dry season from April to September. Previous research by I.H. Suffet *et al.* (1993, unpublished report, "Chemical Contaminant Release Into the Santa Monica Bay: A Pilot Study") and Lau *et al.* (1994) found the DWF in Ballona Creek to be contaminated by polychlerinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), phthalates, and other organic toxicants. Those researchers also reported that WWF discharges from Ballona Creek often had elevated concentrations of contaminants (I.H. Suffet *et al,* 1997, unpublished report, "A Study of Pollutants From the Ballona Creek Watershed and Marina Del Rey During Wet-Weather Flow: Part I. Pollutants Associated With Suspended Solids From the Ballona Creek Watershed and Marina Del Rey;" Wong *et al.,*1997).

This paper describes the models used to estimate the DWF and WWF loads of total suspended solids (TSS), biochemical oxygen demand (BOD), nitrate-nitrogen (NO_3-N), nitrite-nitrogen (NO_2-N), ammonia-nitrogen (NH_3-N), total Kjeldahl nitrogen (TKN), and total phosphorus (TP) for six water years beginning on October 1, 1990, and ending on September 30, 1996. The contaminants studied were selected based on data availability and their potential importance in the degradation of Ballona Creek and Santa Monica Bay beneficial uses. Nitrogen is a limiting nutrient in the coastal waters of Los Angeles and excess loads from urban creeks and storm drains may promote algal blooms in near shore receiving waters (SMBRP, 1994). Suspended solids may reduce light penetration in Santa Monica Bay, which may adversely affect photosynthetic marine plants (Bay *et al.,* 1999).

METHODS

This study uses historical data, field sampling findings, and modeling results to characterize long term DWF and WWF discharges from an urban watershed in Southern California for the 1991 to 1996 water years. The water year definition is consistent with the Los Angeles County Department of Public Works (LADPW) water year with the wet season lasting from October 1 to March 31 and the dry season lasting from April 1 to September 30. This research was conducted in three phases: site selection, DWF data collection and model development, and WWF data collection and model development. The predicted DWF and WWF loads are compared on an annual water year basis, a seasonal basis, and a catchment basis and conclusions about the relative significance of each are drawn.

Site Selection

In this research, the Ballona Creek Watershed (BCW) was studied due to its water quality problems and its importance to water quality in Santa Monica Bay, a National Estuary Program estuary. This system was also chosen because of the dry summer subtropical Los Angeles climate, in which there is a well defined dry season with only a few rainfall events in the summer months. The BCW is composed of three primary drainage catchments: the Ballona Creek, the Sepulveda Channel, and the Centinela Creek catchments (Figure 1). The Ballona Creek, Sepulveda Channel, and Centinela Creek catchments have areas of 21,670, 6,134, and 2,376 hectares, respectively. Ballona Creek drains a heavily urbanized watershed containing portions of downtown Los Angeles. The Creek begins as a covered storm drain eventually becoming an open, concrete lined, trapezoidal channel with a bottom width of 25 to 60 meters. As it travels westward through Los Angeles towards the coast, additional storm drains contribute flow and

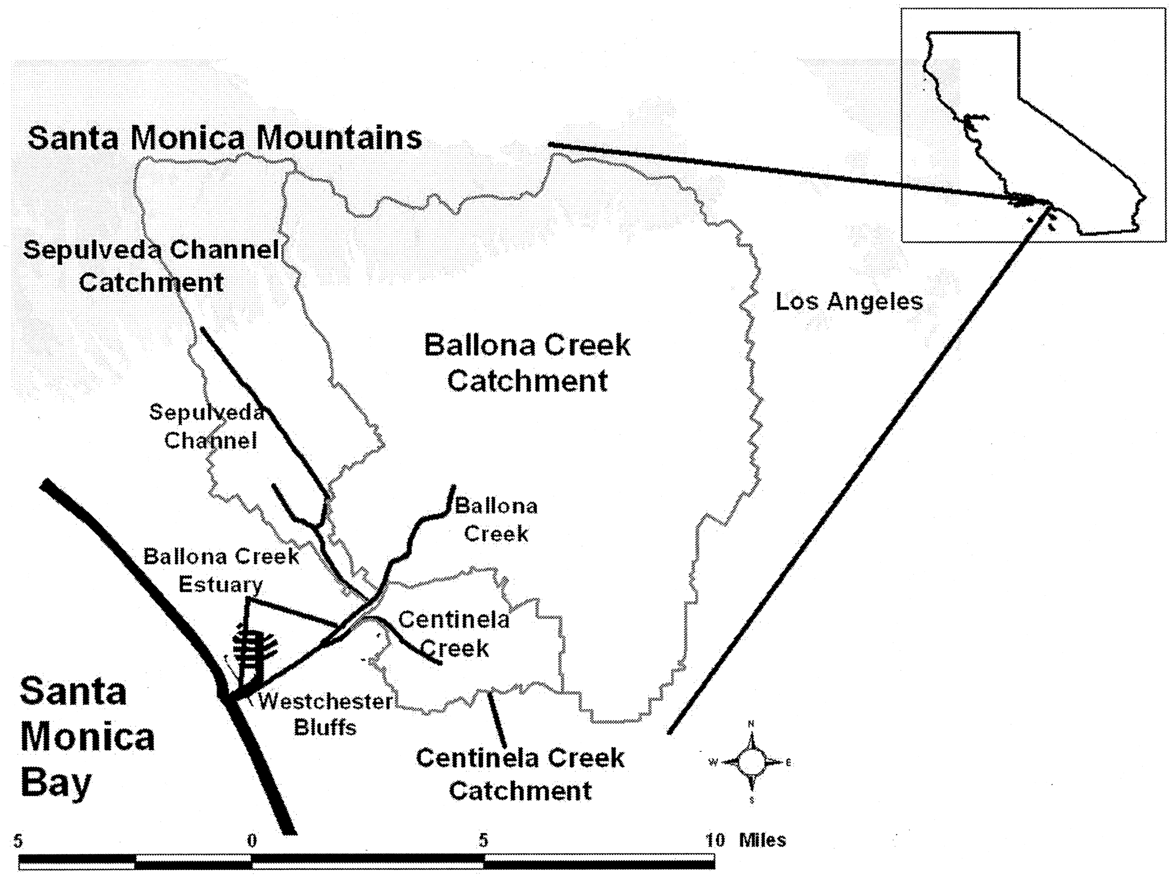

Figure 1. The Ballona Creek Watershed.

pollutants. Ballona Creek has been found to be the most significant source of nonpoint source pollution to the Santa Monica Bight (I.H. Suffet *et al.,* 1997, unpublished report; Wong *et al.,* 1997).

Pollutant Loading Models

Two modeling approaches were utilized to characterize the annual load of pollutants in DWF and WWF. Dry weather flow pollutant loading was evaluated using an empiric model. In urban systems, DWF is a function of base flow, permitted commercial and industrial discharges, and outdoor residential water use. These sources can be relatively unpredictable making physically-based deterministic simulation difficult. Urban DWF loads are therefore assessed using empiric techniques. Wet weather flow pollutant loading was evaluated using a deterministic model. As part of the Urban Security Initiative at Los Alamos National Laboratory (Heiken *et al.,* 1999), storm water runoff models for the BCW were developed using the USEPA Storm Water Management Model (SWMM) (Huber and Dickinson, 1988). Those SWMM models were used in this study with an event mean concentration (EMC) procedure (Huber and Dickinson, 1988) to simulate annual and seasonal runoff quality.

The EMC procedure was used because the goal of this research is a long term evaluation of storm water impacts, not an intrastorm evaluation. Use of EMCs is appropriate for most long term studies of storm water impacts on receiving waters because most large receiving water bodies respond slowly to storm inflows compared to the rate of change of contaminant concentrations during a storm event (Charbeneau and Barrett, 1998). Under these circumstances, the event load is more important than the exact contaminant concentrations during the storm event. This is especially true for nutrients and solids, but less so for contaminants where acute toxicity is important. In most cases, the total load estimated with EMCs for a long term simulation can be as accurate as that obtained from more complex models (e.g., buildup/washoff).

Dry Weather Flow Model

The empiric DWF model of the BCW is based on the historic flow record for Ballona Creek, recorded at 15-minute to hourly increments since 1928 at Station F38C-R. The data obtained were summarized as the mean daily flow rates from the LADPW for the 1991 to 1996 water years. The stream gage is located upstream of the confluences of Sepulveda Channel and Centinela Creek with Ballona Creek and thus represents the flow from the Ballona Catchment only. Historical flow records for Sepulveda Channel and Centinela Creek are not available. Therefore, flow measurements of the three catchments were included in a field project during the summer of 1999. The goal was to develop a relationship between the DWF rate in Ballona Creek and the DWF rates in Sepulveda Channel and Centinela Creek assuming the ratios of DWF in Ballona to the DWF in Sepulveda and Centinela are nearly constant. The measurements indicated the ratio of DWF in Ballona to the DWF in Sepulveda and Centinela to be approximately 25 percent and 4 percent, respectively. These ratios were then used to estimate the historical DWF in Sepulveda Channel and Centinela Creek, corresponding to the recorded DWF rate at the Ballona Creek stream gage for the six water years in the study.

The DWF was estimated from the LADPW mean daily flow record using the sliding interval, base flow separation method (Pettyjohn and Henning, 1979). The water quality characteristics of the DWF were established using two sources of water quality data. One source was the Santa Monica Bay Urban Runoff Database (SMBURD) compiled by Dr. Michael K. Stenstrom of the University of California, Los Angeles (UCLA). The other source was the results of water quality monitoring in the BCW during the summer of 1999. The SMBURD database contains water quality data collected over a period of 20 years by 15 different agencies with responsibility for local water quality in Southern California. The 1999 summer water quality monitoring effort was organized to supplement the SMBURD database and account for current conditions in the system. Current conditions were evaluated by comparing the concentrations of ammonia and nitrate in the 1999 summer monitoring data to the SMBURD data. These constituents were compared because they are the most prevalently characterized nutrients in the SMBURD database and nitrogen is the limiting nutrient in Santa Monica Bay (SMBRP, 1994).

During the summer 1999 effort, samples were collected on six days in June, July, and August. For this study, three sampling sites were targeted: (1) Ballona Creek upstream of the Sepulveda Channel and Centinela Creek confluences; (2) Sepulveda Channel immediately upstream of its confluence with Ballona Creek; and (3) Centinela Creek upstream of its confluence with Ballona Creek. These three sites were chosen to represent the outlets from the Ballona, Sepulveda, and Centinela catchments and to correspond to previous sampling efforts (I.H. Suffet *et al.,* 1993, unpublished report; Lau *et al.,* 1994; I.H. Suffet *et al.,* 1997, unpublished report; I.H. Suffet and M.K. Stenstrom, 1999, unpublished report, "A Study of Pollutants From the Ballona Creek Watershed During Wet-Weather Flow"). By placing the sampling locations at the outlet of the three catchments, the total DWF pollutant contributions from each catchment can be characterized. Each sample was analyzed for TSS, BOD, NO_3-N, NO_2-N, NH_3-N, TKN, and TP using standard methods (APHA, 1998).

The SMBURD database was queried for TSS, BOD, NO_3-N, NO_2-N, NH_3-N, TKN, and TP data for the Ballona Creek, Sepulveda Channel, and Centinela Creek catchments. The sample sites used from SMBURD matched the sites sampled in the summer of 1999. Data retrieved from SMBURD were defined as wet weather or dry weather, using the available rainfall record, and the dry weather data were then combined with the summer 1999 monitoring data to calculate the contaminant concentrations in each catchment. As in other urban runoff studies (Athayde *et al.,* 1983), the data were assumed to follow a log normal distribution. A log-normal distribution was used for each parameter to minimize the considerable errors generated in load calculations by using the improper probability distribution for urban runoff concentrations from a censured dataset as discussed in Van Buren *et al.* (1997).

The DWF load from each catchment was calculated according to

$$W = \sum C_m \times V_j / 10^6 \qquad (1)$$

where W is the load over a prescribed period of time (kg), C_m is the median concentration at the site of interest (mg/L), and V_j is the DWF volume for the period of interest (L). This approach is similar to the sample mean approach listed in Mukhopadhyay and Smith (2000) in which the mean concentration and the average flow on each given day are multiplied and then summed over the period of interest. Because the goal was an estimate of long term pollutant loadings, the median concentration at each location was used with the total volume of flow for the dry and wet season to characterize the seasonal and annual loading in the system. Furthermore, daily concentration data were not available for the period of the simulation.

Wet Weather Flow Model

The BCW WWF models were developed using SWMM with an EMC procedure. A separate model was developed for each of the three primary catchments that compose the BCW so that the relative pollutant contribution from each could be evaluated. In all, 2,899 storm drains with a combined length of 365 km were digitized from LADPW as-built drawings into an ArcView geographic information system (GIS) environment (ESRI, 1998). The three catchments were delineated into 1,897 subcatchments based on U.S. Geological Survey digital elevation models (USGS, 2000), drainage maps (Bill DePoto, LADPW, January 1999, personal communication), roadways (ESRI, 2000), and 1993 Southern California Association of Governments (SCAG) land use data (SCAG, 2000). The land use data obtained from SCAG were categorized according to a modified Anderson Level III/IV classification. This classification was aggregated into 10 land classes to be simulated in SWMM. The breakdown of areas of aggregated land use within each catchment is shown in Table 1. The BCW is dominated by high density single family residential land use, while the amount of water bodies is minimal.

The RUNOFF Block of SWMM was used to simulate the runoff quantity and quality from each catchment to a specified inlet. Runoff quality simulation with the EMC procedures requires the input of appropriate flow weighted EMCs for each of the pollutants for each of the land uses being simulated. The EMCs used in this study were obtained from the LADPW storm water monitoring program (LADPW, 2000). The LADPW has been consistently monitoring Los Angeles County storm water runoff quality at several sites including Ballona Creek since 1996. Part of the LADPW storm water monitoring program is the monitoring of runoff from predominantly single land use catchments. Eight catchments were monitored in which one land use comprised greater than 50 percent of the total catchment area. The number of storms monitored at each site ranged from 24 to 67. The median concentrations for each constituent of concern from the single land use catchments were used in the SWMM models. Using a median EMC from multiple monitored runoff events is appropriate for long term simulations even though EMCs typically vary from storm to storm. Table 2 displays the ten land uses simulated in the SWMM models and the corresponding median EMC used for each contaminant simulated. Two additional land uses, water and other urban, were simulated in SWMM. Because no runoff is generated off water surfaces, no EMC was necessary for that land use. The EMC for the other urban land use was defined as the average of commercial, transportation, and light industrial land uses.

RESULTS

Preliminary Model Verification

To verify the output of the storm water models, the total runoff volume for one wet season was predicted and compared to observed runoff records. Rainfall data recorded at the Los Angeles Civic Center (LACC) gage located in the Ballona Creek Catchment drove the simulation for the 1997 wet season dating from October 1, 1996, to March 31, 1997. During this time,

TABLE 1. Land Use Breakdown of Ballona Creek, Sepulveda Channel, and Centinela Creek Catchments.

Land Use	Ballona Catchment Area (ha)	Sepulveda Catchment Area (ha)	Centinela Catchment Area (ha)
High Density Single Family Residential	9,666	2,273	1,093
Mixed Residential	1,514	12	50
Multifamily Residential	2,826	608	241
Industrial	892	131	248
Institutional	641	309	42
Urban Vacant	2,476	1,987	281
Transportation	396	228	101
Commercial	3,043	488	312
Water	112	65	0
Other Urban	104	33	8
Total	21,670	6,134	2,376

TABLE 2. Wet Weather Flow Median Event Mean Concentrations (mg/L) From the LADPW Storm Water Monitoring Program During 1994 to 2000.

Land Use	TSS	NO_3-N	NO_2-N	NH_3-N	TKN	TP	BOD
High Density Single-Family Residential	61	0.46	0.05	0.25	2.00	0.32	15.0
Multifamily Residential	24	0.80	0.05	0.24	1.50	0.14	9.0
Mixed Residential	40	0.44	0.06	0.33	1.70	0.18	14.0
Industrial	129	0.52	0.06	0.26	2.30	0.30	17.0
Institutional	61	0.48	0.05	0.15	1.30	0.23	12.0
Urban Vacant	18	0.94	0.05	0.05	0.68	0.05	5.0
Transportation	50	0.40	0.06	0.14	1.30	0.32	19.0
Commercial	53	0.43	0.07	0.25	2.20	0.28	24.0
Other Urban	77	0.43	0.06	0.22	1.90	0.30	20.0

16 runoff producing storm events were recorded. The total observed storm water runoff volume for the 16 events from October 1, 1996, to March 31, 1997, was calculated to be 1.2 x 10^9 ft^3 (3.4 x 10^7 m^3) from a 15-minute flow record collected at a flow gage located on Ballona Creek. The SWMM simulation predicted 1.13 x 10^9 ft^3 (3.2 x 10^7 m^3) over the same time period, an underprediction of less than 10 percent. Although the predicted wet season volume is close to the observed, the validity of the model is still questionable without further calibration. The primary problem with adequately calibrating and validating the model is the lack of adequate spatial coverage of rainfall. Using a single rain gage to represent the rainfall over the Ballona Catchment is not appropriate. However, the comparison of the 1997 wet season predicted and observed volumes suggests the models are appropriate for long term evaluations, especially for relative comparisons.

The prediction of water quality at the BCW outlet was also tested using the land use specific EMCs. Seven storm events from the 1996 to 1997 wet season that corresponded to events the LADPW monitored were simulated. Besides land use specific monitoring, the LADPW also has mass emission stations at several of the larger catchments in the Los Angeles area including the Ballona Creek Catchment. For each contaminant simulated, the average predicted EMC was compared with the average observed EMC at the LADPW Ballona Creek mass emission station. The results of the comparison are shown in Table 3. The average predicted EMCs are within 0 to 33 percent of the observed EMCs for each contaminant simulated except TSS, BOD, and TP, which are 62 percent, 60 percent, and 52 percent different than the observed EMCs, respectively. Although these results indicate good agreement between the model and LADPW data for most constituents, the models are consistently underpredicting the EMCs, which when considered in tandem with the flow underpredictions are most likely producing an underestimate in WWF pollutant loading. The model should also only be used for long term storm loading analyses and not prediction of individual storm events, because using median, observed EMCs in a simulation produces accurate predictions over the long term, but less accurate predictions on a storm event basis.

TABLE 3. Comparison of Average Observed and Predicted Event Mean Concentrations for Seven Runoff Events From the Ballona Creek Catchment for the 1996 and 1997 Wet Season.

Contaminant	Average Observed EMC (mg/L)	Average Predicted EMC (mg/L)	Percent Difference (percent)
TSS	109	41	62.1
NO_3-N	0.480	0.441	8.1
NO_2-N	0.06	0.04	33.3
NH_3-N	0.18	0.18	0.0
TKN	1.7	1.43	15.9
Dissolved P	0.17	0.15	9.8
TP	0.42	0.20	51.7
BOD	29	11	59.9

The estimation of DWF in Ballona Creek during the period of study ranged from 8 x 10^{-2} m^3/sec to 2 m^3/sec, while the DWF in Sepulveda Channel and Centinela Creek ranged from 2 x 10^{-2} m^3/sec to 5.5 x 10^{-1} m^3/sec and from 3 x 10^{-3} m^3/sec to 8 x 10^{-2} m^3/sec, respectively. Table 4 shows the average contaminant concentration from each catchment during the DWF sampling protocol of 1999. Contaminant concentrations from the three catchments are similar except for

TSS in Sepulveda Channel, which is three times the concentration in both of the other channels. Because the concentrations from each catchment are similar, the relative importance of each catchment to the total DWF pollutant load can be assessed using the flow volume information. The monitoring results indicate that Centinela Creek DWF volume is negligible. Therefore, the DWF volume and pollutant load contributions from the Centinela Creek catchment were not included in the results shown below unless otherwise stated. Figure 2 shows the comparison of the ammonia and nitrate concentrations in the SMBURD and in the summer 1999 monitoring protocol. The gray area in each box plot represents the 95 percent confidence interval. Although nitrate concentrations varied more in the SMBURD data, nitrate and ammonia concentrations in the summer 1999 monitoring protocol are similar to those in the SMBURD. This result indicates DWF from the watershed has been a consistent and perennial source of pollutants to the downstream receiving waters and validates the combination of the two water quality datasets for the calculation of the annual load.

TABLE 4. Average Dry Weather Flow Contaminant Concentrations (mg/L) Based on Summer 1999 Monitoring Results.

Contaminant	Ballona Creek	Sepulveda Channel	Centinela Creek
TSS	13.8	31	13.6
NO_3-N	1.11	2.03	0.54
NO_2-N	0.02	0.06	0.02
NH_3-N	0.29	0.30	0.30
TKN	3.17	3.55	4.98
TOTP	0.85	0.47	0.56
BOD	10.1	12.5	10.8

The DWF estimation procedures were partly verified by comparing the estimated 1997 water year wet season WWF volume to an estimate based on the more detailed 15-minute flow record. The DWF reduction approach estimated the 1997 WWF volume to be 36 x 10^6 m^3, which was less than 7 percent different than the 33.7 x 10^6 m^3 value produced from the more detailed 15-minute flow record. The 1997 water year was the only year used to assess the DWF performance because it was the only water year having a continuous set of 15-minute flow data throughout the wet season.

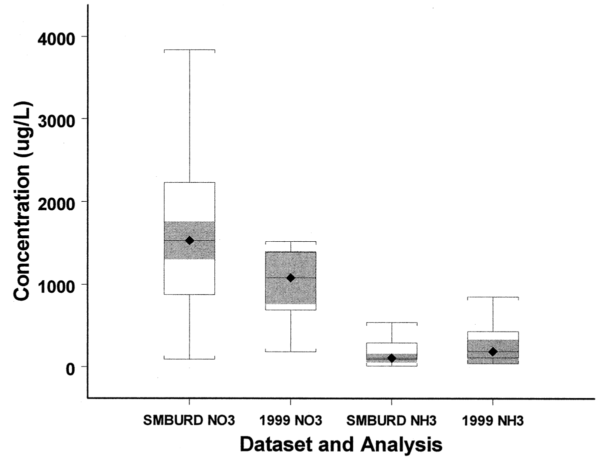

Figure 2. Nitrate and Ammonia Concentrations in the SMBURD and Summer 1999 Monitoring Protocol.

DWF Versus WWF Comparison

Figure 3 shows the DWF and WWF volume per water year from 1991 to 1996. The annual discharge volume from Ballona Creek is predominantly from WWF. The fraction of annual discharge volume from WWF ranges from 75 percent to over 90 percent. Given that the SWMM WWF model is underpredicting runoff volumes these results indicate WWF is the major source of annual runoff. Dry weather flow, as expected, is more significant during the dry season. During the dry season, approximately 70 percent of the discharge volume on average is due to DWF, while less than 10 percent of the discharge volume on average during the wet season is from DWF. Although the SWMM models are slightly underpredicting flow volumes, the dry season DWF contribution is still significant due to the magnitude of the DWF dry season contribution relative to WWF and the low number of rainfall events in the dry season. The annual DWF volume was fairly consistent. Therefore, the variation in the DWF contribution to the total annual volume of flow was dependent on the highly variable volume of WWF (i.e., in relatively low precipitation years the DWF contribution was higher and in relatively high precipitation years the DWF contribution was lower).

Table 5 shows a comparison of the average annual pollutant load from DWF and WWF. The results are consistent with the volume results showing the WWF pollutant contribution to be the most significant on an annual basis. On average, WWF accounts for the majority of the average annual load of each constituent studied. During the dry season, DWF load is important primarily because of the lack of rainfall to generate WWF loads. Table 6 displays the average

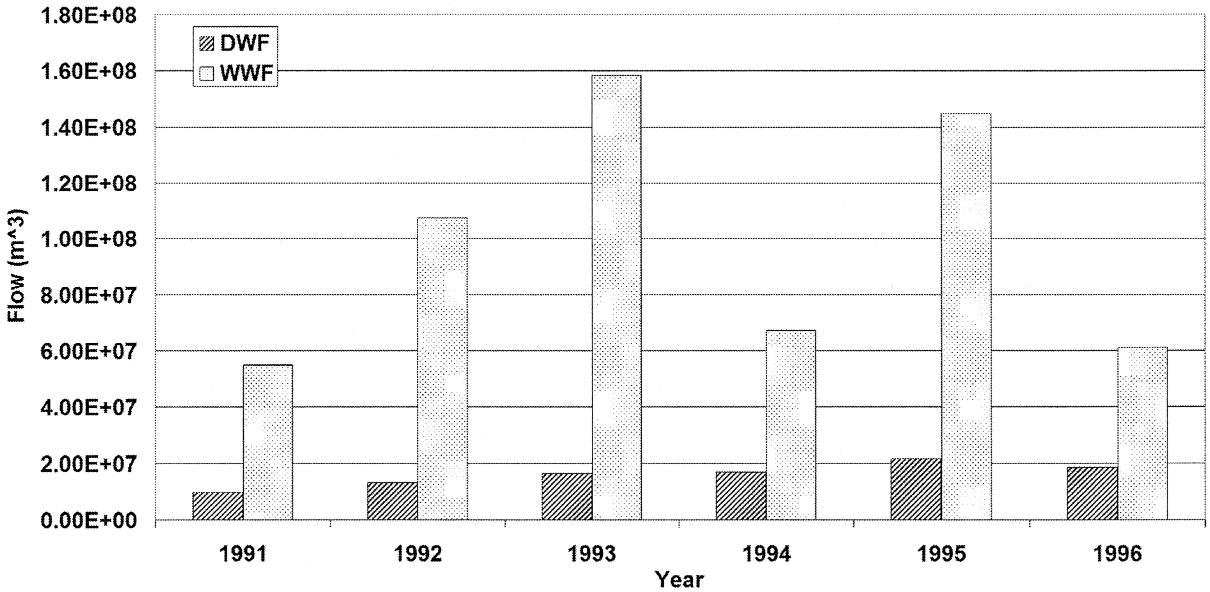

Figure 3. Annual Total Volumes of DWF and WWF.

dry season pollutant loads. The importance of DWF relative to WWF is evident, with high fractions of the dry season loads of BOD (34 percent), NO_3-N (83 percent), NO_2-N (66 percent), NH_3-N (50 percent), TKN (75 percent), and TP (42 percent) coming from DWF. The large proportion of the total dry season load attributable to DWF is significant, especially for NO_3-N and NH_3-N, even in light of the underprediction of flow and pollutant concentrations in the WWF model.

TABLE 5. Comparison of Average Annual DWF and WWF Contaminant Loads.

	Average Annual DWF Load (kg)	Average Annual WWF Load (kg)	Percent From DWF
TSS	91,940	4,944,380	2
BOD	56,780	1,361,090	4
NO_3-N	27,000	53,800	33
NO_2-N	900	5,200	15
NH_3-N	1,800	21,100	8
TKN	46,600	168,600	22
TP	1,500	24,000	6

While WWF is the dominant pollutant source on an annual basis from the entire watershed, the contribution from DWF relative to WWF becomes more significant when the individual catchments are considered. Table 7 shows the load contribution of the constituents studied from the Ballona Creek Catchment DWF and WWF, Sepulveda Channel DWF and WWF, and Centinela Creek WWF. The predominant source is still WWF from Ballona Creek, but the total nitrogen load in DWF from that catchment is similar to the WWF load from both Sepulveda Channel and Centinela Creek. The higher DWF loads from Ballona Creek compared to WWF loads from Sepulveda Channel and Centinela Creek suggest that management action for Ballona Creek DWF may be more appropriate than management action for WWF control from Sepulveda Channel and Centinela Creek. Further comparisons of the relative loads from the three catchments would provide additional guidance for water quality management in the BCW.

TABLE 6. Comparison of Average Dry Season DWF and WWF Contaminant Loads.

	Average Dry Season DWF Load (kg)	Average Dry Season WWF Load (kg)	Percent From DWF
TSS	46,000	221,700	17
BOD	31,600	61,200	34
NO_3-N	12,900	2,500	83
NO_2-N	400	200	66
NH_3-N	900	900	50
TKN	23,300	7,600	75
TP	800	1,100	42

TABLE 7. Average Annual DWF and WWF Loads From Each Catchment.

Catchment	TSS (kg)	NO_3-N (kg)	NO_2-N (kg)	NH_3-N (kg)	TKN (kg)	TP (kg)	BOD (kg)
Ballona Creek DWF	43,800	20,000	800	1,400	36,000	1,000	44,800
Sepulveda Creek DWF	48,200	7,000	100	400	10,800	500	12,000
Centinela Creek WWF	469,800	4,200	400	1,900	15,000	2,200	119,800
Sepulveda Creek WWF	769,900	10,500	900	3,000	25,600	3,600	204,100
Ballona Creek WWF	3,704,700	39,000	3,900	16,200	128,100	18,300	1,037,100

DISCUSSION

In this preliminary modeling study of the BCW, WWF was found to contribute 67 percent or more of the average annual pollutant load for each of the contaminants considered. Conversely, in the dry season when rainfall is infrequent and WWF volume is low, the importance of DWF as a source of pollutants increases. On average, DWF accounted for a considerable proportion (i.e., greater than 34 percent) of the pollutant load during the dry season for the contaminants in the study except for TSS. The spatial analysis of loads indicates the Ballona Creek Catchment is clearly the most important nonpoint pollution source relative to the Sepulveda Channel and Centinela Creek Catchments. Wet weather flow from the Ballona Creek Catchment is the predominant source of pollutants from the watershed, and DWF from the Ballona Creek Catchment is as important a source of nitrogen as WWF from the other catchments. These results are similar to those of Stephenson and Green (1988), who calculated DWF and WWF loads for two urban South African catchments. In that study, Stephenson and Green (1988) determined that the WWF pollutant loads were 3.6 to 5.3 times the DWF loads. In this research, the WWF load to DWF load ratio ranges from 2 to 54 depending on the parameter studied. The greater range of values in this research is most likely the result of the inclusion of a wider range of constituents. Stephenson and Green (1988) only calculated DWF and WWF loads for TDS, while in this research, loads for some parameters that are known to be significantly transported in WWF (e.g., TSS) (Athayde *et al.,* 1983) are calculated.

This preliminary modeling study indicates for certain development infrastructure climatological combinations, the contribution of DWF pollutant loading may be comparable in magnitude to WWF for large watersheds over seasonal time scales. Even with the error in the modeling described in the paper, the results provide enough support for the need to consider management strategies for DWF in highly urbanized environments. Based on this study, additional observational and modeling work is needed to reduce the uncertainty of the results and to better understand the pollutant loading and ecological response differences to DWF and WWF. Only then can informed policy and management strategies and treatment approaches be developed. This preliminary modeling study indicates that the importance of DWF versus WWF as pollutant loading sources shifts depending on the time of the year and on the spatial scale of the analysis. The magnitude of the differences between WWF and DWF is large enough to support that conclusion even when considering the modeling error. Improved models will help clarify relative importance of WWF and DWF. Even though each flow type can be a considerable source of pollutants, management plans should not be based solely on the magnitude of the loads. Due consideration must be given to the assimilative capacity of the receiving water (USEPA, 1997b). In most TMDL analyses, the assimilative capacity is based on a critical flow condition, which often occurs in the dry season (USEPA, 1997c). In coastal watersheds, the receiving waters are tidally influenced and the establishment of a critical flow condition is difficult due to the dynamic nature of the tides. The determination of receiving water impacts of urban runoff loads into coastal water bodies is therefore difficult. The receiving waters of the BCW are tidally influenced and this complicates the evaluation of relative importance of DWF and WWF receiving water impacts in this system.

The receiving water impacts of the nutrient load in DWF and WWF discharged from the BCW are not clearly understood. Several issues remain to be resolved. First, to assess the water quality impacts of DWF versus WWF, the affected receiving water must be clearly defined. In the watershed studied in this research, there are two potential receiving waters: (1) Santa Monica Bay, a National Estuary Program estuary; and (2) the Ballona Creek Estuary. The receiving water for a large fraction of the DWF pollutant load from the BCW is most likely the Ballona Creek Estuary. The City of Los Angeles (1992) indicated the residence time of dry weather flow entering the estuary is roughly 19 to 20 days. The estuarine water quality response time to nutrient inputs is on the order of days to weeks (Donigian and Huber, 1991), so it may be assumed that the Ballona Creek Estuary responds to a large portion of the DWF load. The ultimate fraction of DWF pollutant load that passes through the estuarine system into Santa Monica Bay is unknown but is assumed to be relatively small for settleable contaminants and contaminants that will be fixed by sediment bound algae. Another consideration is the amount of contaminant retained during dry weather that is eventually flushed out to the Bay by the high flow rates during wet weather.

The ultimate receiving water for a large fraction of the WWF pollutant load, on the other hand, is Santa Monica Bay. Observations of the WWF dynamics in the area of the Ballona Creek Estuary and the Ballona Creek outlet to Santa Monica Bay indicated that a large proportion of the WWF load reaches the Bay (I.H. Suffet *et al.,* 1997, unpublished report). The impact of the WWF pollutant load on the Ballona Creek Estuary is probably minimal because the residence time is so short. Scouring and habitat destruction from the high flow rates and flow volumes during wet weather will more likely have a greater impact on the Ballona Creek Estuary than the WWF contaminant concentrations.

The considerations briefly discussed here indicate the complexity of watershed management and the difficulties inherent in developing a watershed management plan. This research indicates the need to consider DWF when formulating watershed management plans for urban Southern California watersheds. Initially, the comparison of the annual DWF and WWF pollutant loads suggested the need to focus management on WWF, but after factoring in the seasonal distribution of the loads, the importance of DWF during the dry season became apparent. This phenomenon may be true in other urbanized Southern California watersheds where the annual and dry season rainfall is low. The significance of DWF as shown by the results indicates the need to consider its control or treatment. Municipalities in the region have recognized this need and several treatment practices are already in place in the Los Angeles area. For example, DWF has been pumped from some storm drains to a centralized wastewater treatment plant in Los Angeles (ASCE, 1999), and in December 2000, the City of Santa Monica opened a treatment facility designed to treat DWF from residential and commercial areas (Antich *et al.,* 2002).

CONCLUSIONS

A significant body of research has shown that WWF pollutant contributions to receiving waters are an important source to be considered when constructing watershed management plans. Storm drainage systems in large urban centers (e.g., Los Angeles) can also have significant DWF from nuisance and incidental sources, and the DWF component of the pollutant load discharged from the drainage system may be significant. A relative comparison of DWF and WWF loads from the BCW in Los Angeles was presented. On an annual basis, WWF was found to contribute the majority of the discharge volume and pollutant load. On a seasonal basis, DWF was found to be an important source of discharge volume and pollutant load during the dry season (April 1 to September 30) when rainfall is infrequent. This work indicates the management of the BCW may require an integrated plan accounting for both DWF and WWF.

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