Trace Metal Pollutant Load in Urban Runoff from a Southern California Watershed

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Abstract: In order to implement efficient and effective management strategies for coastal water quality in Southern California, it is important to consider the relative pollutant contributions from urban dry-weather flow (DWF) and wet-weather flow (WWF). This study uses both historical flow coupled with water quality monitoring data and computer modeling to characterize the annual DWF and WWF discharges from an urban catchment in Los Angeles, Calif. The DWF and WWF pollutant loading of the trace metals copper, lead, nickel, and chromium for 6 water years dating from 1991 to 1996 is predicted. The results indicate that DWF contributes a considerable amount of flow and pollutants. Approximately, 9–25% of the total annual Ballona Creek flow volume is DWF. The simulations indicate DWF accounts for 54, 19, 33, and 44% of the average annual load of total chromium, copper, lead, and nickel, respectively. In the dry season, the simulations indicate DWF accounts for 89, 59, 58, and 90% of the load of total chromium, copper, lead, and nickel, respectively. This research suggests DWF controls may be an important part of pollution mitigation plans for urban stormwater drainage systems in Southern California.

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Introduction

Increased human populations in coastal areas have placed increased pressure on coastal ecosystems. In 1960, approximately 80 million people lived in coastal areas of the United States. As of 1990, 112 million people lived in United States coastal areas. The Southern California Coast was one of the regions of highest population change during this period (Culliton et al. 1990). The influx of people was accompanied by increased urban development; Los Angeles, Orange, and San Diego counties were among the top ten counties in the nation in construction of new single and multifamily homes and commercial and industrial buildings in the period from 1970 to 1989 (Culliton et al. 1992). The increased urban development in Southern California coastal watersheds, as in other coastal watersheds, changed the natural drainage of those systems, increased the amount of impervious area, and altered watersheds such that they became exporters of anthropogenically produced contaminants in urban runoff (United States Environmental Protection Agency 1993; Santa Monica Bay Restoration Project 1994). As a result of this urban runoff loading and other sources, the water quality in many Southern California coastal systems is impaired as evidenced by their placement on the California list for Total Maximum Daily Load (TMDL) development (California Environmental Protection Agency, State Water Resources Control Board, 1999).

Urban runoff in Southern California's Mediterranean climate can be divided into wet-weather flow (WWF) or dry-weather flow (DWF). In our study, we define WWF as the surface runoff produced by precipitation events. The DWF is the baseflow resulting from groundwater inflow, permitted discharges, illicit connections to the storm sewer system, excess irrigation, automobile washing, and other residential and commercial uses. The WWF discharges from urban storm drains into receiving waters have long been recognized as a significant source of pollutants and cause of water-quality degradation (APWA 1969; Field and Turkeltaub 1981; Athayde et al. 1983; Heaney and Huber 1984). In the Los Angeles area, historical creeks and rivers have been modified into concrete-lined storm drains (e.g., Los Angeles River and Ballona Creek). These massive concrete channels direct flow to the ocean throughout the year and the WWF from these systems has been shown to be a significant source of toxic and conventional contaminants to downstream coastal receiving waters (Suffet et al. 1997; Wong et al. 1997; Los Angeles Department of Public Works 1998; Suffet and Stenstrom 1999).

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The impact of urban DWF discharges is less understood. The relative importance of DWF load compared to WWF load is dependent on many factors, but is most likely related to the amount of annual precipitation, frequency of precipitation events, the degree of urbanization (i.e, alteration of land use to commercial, residential, and industrial purposes), the pollutant concentrations in each flow type, and the extent of DWF production due to illicit connections, excess irrigation or other nuisance flows. Southern California has several characteristics that may make DWF an important pollutant source. Southern California has a dry Mediterranean climate characterized by a distinct wet season and low annual precipitation. Annual average rainfall in Los Angeles is 300–330 mm, and the majority of the rainfall occurs in the winter (Santa Monica Bay Restoration Project 1994). Many coastal Southern California watersheds are highly urbanized and these densely populated areas import a large amount of water that is used for residential, commercial, and industrial uses. The City of Los Angeles, for example, imports approximately 80% of its water (Los Angeles Department of Water and Power 1999). Although the majority of this water is discharged to the sanitary sewer system, a considerable proportion may be discharged to storm drain systems following use.

The DWF in the Ballona Creek watershed has also been found to contain elevated concentrations of toxic contaminants. Lau et al. (1994) determined that the DWF effluent from the Ballona Creek system and several other storm drains in the Santa Monica Bay watershed was equivalent to secondary sewage effluent for some parameters including chemical oxygen demand (COD), total suspended solids (TSS), and turbidity and that it exerted a toxic effect on tested marine species. In an associated study, Suffet et al. (1993) found elevated concentrations of organic contaminants in Ballona Creek DWF and noted the potential importance of suspended solids in the transport of polychlorobiphenyl and polynuclear aromatic hydrocarbons. While much of the current regulatory strategies are concerned with nonpoint source contamination of water bodies from WWF, results from the studies mentioned above indicate the toxic potential of DWF in Southern California. Understanding the magnitude of the contaminant load in DWF and WWF allows the appropriate allocation of resources between water quality management alternatives.

An important contaminant in storm drain effluent is heavy metals (Athadye et al. 1983; United States Environmental Protection Agency 1998). Metals in DWF and WWF come from permitted or illicit discharges, surface runoff from industrial facilities, atmospheric deposition, releases due to dissolution from water pipes, or releases during wear of machine parts especially automobiles. Once in receiving waters, metals can accumulate in bottom sediments, bioaccumulate in animal tissues, and affect ecological systems.

There have been no detailed studies comparing the relative importance of DWF and WWF pollutant loads of metals from urban Southern California coastal watersheds. Duke et al. (1999) statistically compared concentrations of select water quality parameters in DWF to concentrations in WWF at locations throughout California including two stations in Ballona Creek. Those researchers found no statistically significant differences between DWF and WWF concentrations in Ballona Creek for total and dissolved copper, lead, and zinc, but indicated the strength of the conclusion was not strong due to low sample sizes. Stephenson and Green (1988) calculated DWF and WWF loads for two urban South African catchments determining that WWF pollutant loads were 3.6–5.3 times DWF loads, but they only calculated DWF and WWF loads for total dissolved solids in a region with greater annual rainfall than Southern California. This paper compares the heavy metal load in DWF and WWF in the Ballona Creek watershed. We simulate the WWF load of total heavy metals using the Storm Water Management Model (SWMM) (Huber and Dickinson 1988). We estimate the DWF load of total heavy metals using an empirically based DWF load model. The model is developed as part of this research.

Methods

This study uses historical data, field sampling protocols, and modeling results to characterize long-term average DWF and WWF discharges from the Ballona Creek watershed. Total suspended solids, chromium (Cr), copper (Cu), lead (Pb), and nickel (Ni) were selected for this study because of their importance in relation to the protection of Ballona Creek and Santa Monica Bay beneficial uses and the availability of the necessary data to create the models. The Ballona Creek system was chosen for this study because it has been placed on the California list for TMDL development for several of the metals studied (California Environmental Protection Agency, State Water Resources Control Board, 1999) and has been determined to be a major source of contaminants to Santa Monica Bay, a National Estuary Program estuary.

Ballona Creek Watershed Description

Fig. 1 shows the major features of the Ballona Creek Watershed. The watershed is located in Southern California, and includes a significant portion of Los Angeles, Calif. Approximately 85% of the 330 km^2 watershed is covered by urban land uses (Wong et al. 1997). The watershed extends north into the Santa Monica Mountains, west into Beverly Hills and Culver City, east into downtown Los Angeles and south to the Westchester Bluffs. The drainage of the watershed can be divided into three subcatchments: the Ballona Creek catchment, Sepulveda Channel catchment, and the Centinela Creek catchment. Ballona Creek, Sepulveda Channel, and Centinela Creek are concrete-lined channels fed by a complex network of storm drains. Sepulveda Channel feeds into Ballona Creek and Ballona Creek flows into the Ballona Creek Estuary. Centinela Creek flows directly into the Ballona Creek Estuary. The Ballona Creek Estuary is an area of significant tidal influence from Santa Monica Bay. The Ballona, Sepulveda, and Centinela catchments account for the majority of the flow into the Ballona Creek Estuary.

Dry-Weather Flow Load Calculation

An empiric model to predict the seasonal DWF pollutant load from the Ballona Creek watershed for the 1991–1996 water years was developed. The model development began with analyzing the historical flow record for Ballona Creek. Flow rates in Ballona Creek have been recorded at 15 min to hourly increments since 1928 at station F38C-R, located at the Sawtelle Avenue Bridge just upstream of the confluence with Sepulveda Channel. The data were obtained as the mean daily flow rates from the Los Angeles Department of Public Works for the 1991 to 1996 water years. Historical flow records for Sepulveda and Centinela 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. The measured ratios of flow between Sepulveda Channel

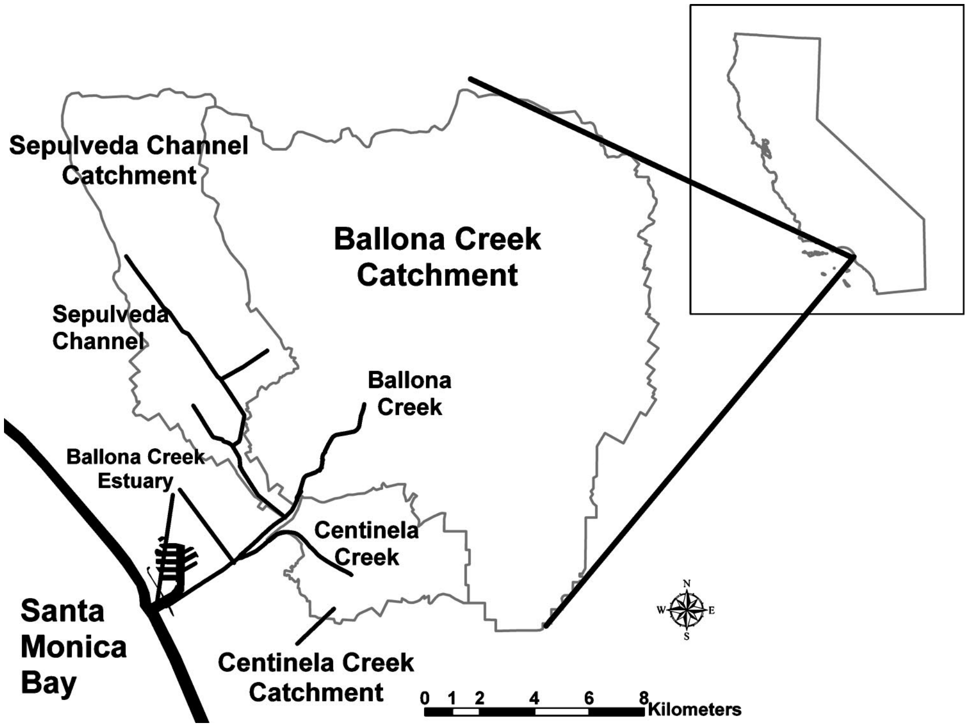

Fig. 1. Ballona Creek Watershed

and Ballona Creek and Centinela Creek and Ballona Creek had an average and standard deviation of 0.27 ± 0.07 and 0.04 ± 0.02, respectively.

In order to determine the yearly load from dry weather runoff conditions, the LADPW mean daily flow data had to be adjusted to remove wet weather conditions. Wet weather flows were removed using the sliding interval base flow separation method (Pettyjohn and Henning 1979). The DWF reduction procedures were partly verified by comparing the estimated 1997 water year wet season WWF volume to an estimate based on the more detailed 15 min flow record. The DWF reduction approach estimated the 1997 WWF volume to be 36×10^6 m^3, which was less than 7% different than the 33.7×10^6 m^3 value produced from the more detailed 15 min flow record.

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 Ballona Creek watershed 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.

During the summer 1999 effort, samples were collected on 6 days in June, July, and August. Samples were collected from three sites within the Ballona Creek watershed at 6 h intervals: (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 (Fig. 2). These three sites were chosen to represent the outlets from the Ballona, Sepulveda, and Centinela catchments and to correspond to previous sampling efforts (Suffet et al. 1993, 1997; Lau et al. 1994; Suffet and Stenstrom 1999). 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 and dissolved and suspended solids concentrations of Cr, Cu, Pb, and Ni. Analytical methods were similar to those used in Suffet and Stenstrom (1999) in a 1998 sampling protocol of WWF. Samples were collected in the field in amber glass bottles, placed in an ice chest until they were brought to the laboratory where they were stored at 4°C until filtration. Samples were filtered using a stainless steel, Teflon-lined Millipore 142 mm Hazardous Waste Filtration System with an integral 1.5 L reservoir. Samples were filtered in 1 L increments using pressure filtration through preweighed 142 mm, 0.7 μm pure glass Toxicity Characteristic leaching procedure (TCLP) filters. The second liter of each sample was collected as filtrate for water quality analyses. Thirty milliliters of each filtrate were placed with 3 drops of trace metal grade concentrated HNO_3 in 30 mL Nalgene low density polyethylene (LDPE) bottles for trace metal analysis. Filters were then dried according to the methods of Capangapangan and Suffet (1998) in which the filter paper is placed on top of folded weighing paper that rests on anhydrous calcium chloride desiccant in a precleaned glass jar. Following drying, each filter was cut into pieces and placed into 250 mL beakers with 20 mL of HCl and 5 mL of HNO_3 for 20 min. After the initial digestion the samples were transferred to a Whatman Number 41 filter paper and washed with 5 mL of hot HCl followed by 20 mL of hot water. The resulting filtrate was collected in a 100 mL volumetric flask. The remaining digestate and filter were then transferred back into the beaker with 10 mL of HCl and digested for another 10 min. This second digestion was then transferred to another Whatman Number 41 filter and washed with 25 mL of hot water. The resulting filtrate was collected in the same 100 mL volumetric flask. The final solution was then diluted to 100 mL total volume. From this solution a 15 mL aliquot was transferred

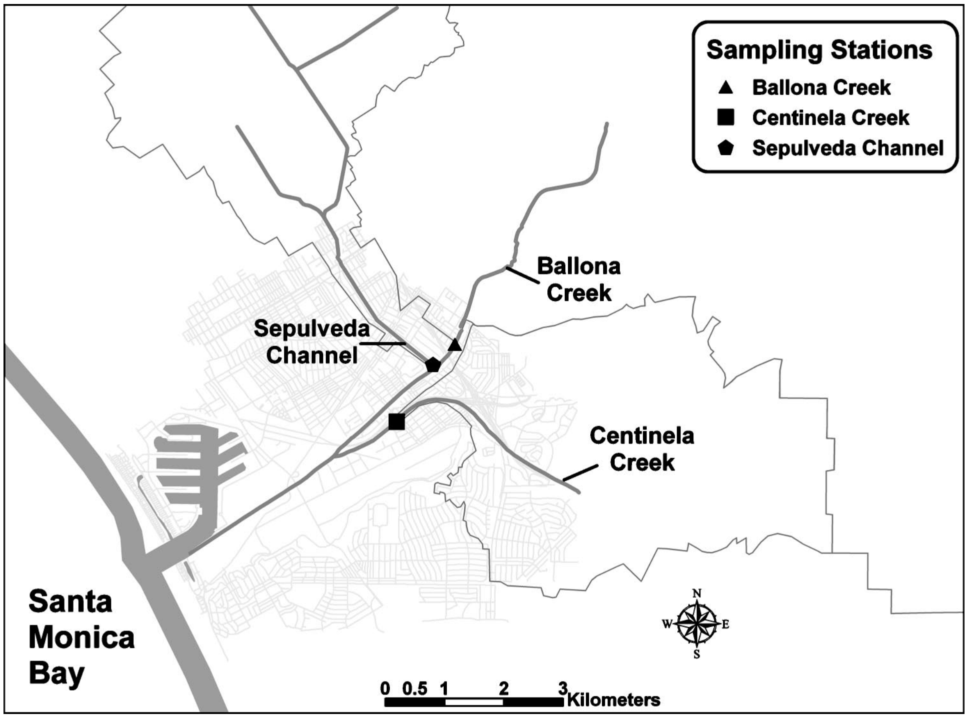

Fig. 2. Sample sites within Ballona Creek Watershed

with 15 mL of water to a 30 mL Nalgene LDPE bottle for trace metal analysis. The filtrates and suspended solids samples were analyzed for trace metals by inductinely coupled plasma–atomic emission spectroscopy according to *EPA Method 3120.B*. The metals concentrations in the filtrate represent the dissolved phase. Total recoverable metals were calculated as the sum of dissolved and suspended solids concentrations of metals.

The SMBURD database was queried for TSS and total Cu, Cr, Pb, and Ni data for the Ballona Creek, Sepulveda Channel, and Centinela Creek catchments. Total metal concentrations were used as the parameter of study due to the low amount of dissolved metals concentration data in the SMBURD database. 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. Samples reported below the detection limit were transformed to half the detection limit. As in other urban runoff studies (Athayde et al. 1983), the data were assumed to follow a log-normal distribution. In this study, 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). Table 1 shows the average, median, and standard deviation of each metal in the dataset. Median concentrations of Cu, Pb, and Ni are similar in Ballona Creek and Sepulveda Channel but lower in Centinela Creek. Median Cr concentrations are similar in Centinela Creek and Ballona Creek but lower in Sepulveda Channel. Because the DWF in Centinela Creek is less than 3% of the combined DWF in Ballona Creek and Sepulveda Channel and the concentrations for the majority of parameters studied are lower in Centinela Creek, the Centinela DWF was considered negligible and was not included in subsequent analyses.

The DWF load from each catchment was calculated according to

$$W = \sum C_m \times V_j / 10^6 \tag{1}$$

where W=load over a prescribed period of time (kg); C_m=median concentration at the site of interest (mg/L); and V_j=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 our 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. Fur-

Table 1. Mean, Median, and Standard Deviation of Dry-Weather Flow Total Metal Concentrations (μg/L) in Ballona Creek Watershed Catchments

Location	Total Cr	Total Cu	Total Ni	Total Pb
Ballona Creek				
Mean	38	23	16	21
Median	15	16	10	10
Standard deviation	87	28	19	28
Sepulveda Channel				
Mean	4	16	37	8
Median	5	14	9	8
Standard deviation	3	13	103	4
Centinela Creek				
Mean	11	12	16	11
Median	10	5	5	5
Standard deviation	5	9	28	20

Table 2. Total Area and Assigned Percent Imperviousness for Each Land Class Included in Ballona Creek Watershed Storm Water Model

Land use	Area (ha)	Percent imperviousness (%)
Commercial	3,843	92
High-density single family residential	13,033	68
Mixed residential	1,577	75
Multifamily residential	3,675	80
Industrial	1,272	91
Institutional	993	30
Urban vacant	4,744	0
Water	177	0
Transportation	726	92
Other/unknown urban	145	80

thermore, daily concentration data were not available for the period of our simulation.

Wet-Weather Flow Simulation

Stormwater models of the Ballona Creek watershed were developed as part of a larger environmental modeling project performed at Los Alamos National Laboratory (Heiken et al. 1999). These models were developed using the U.S. Environmental Protection Agency (EPA) SWMM (Huber and Dickinson 1988). Separate stormwater models were developed for the Ballona, Sepulveda, and Centinela Catchments (Burian et al. 2000). The development of the stormwater models required digitizing 3,000 storm drains and delineating over 2,000 subcatchments using information obtained from microfiche as-built construction drawings of the storm drainage system and drainage maps stored at the LADPW. Other data necessary to develop the models included United States Geological Survey digital elevation models and 1993 land use data from the Southern California Association of Governments (SCAG). The land use data obtained from SCAG were categorized according to the Modified Anderson Level III/IV classification. This classification was aggregated into ten land use classes selected for inclusion in the stormwater quality simulation. The breakdown of land use for the three catchments is shown in Table 2.

The WWF quality was simulated in SWMM by attributing an event mean concentration (EMC) to each of the land uses simulated. The EMC procedure was used because the goal of this research is a long-term prediction of seasonal and annual loads, not an intrastorm evaluation, which would require a more complicated modeling approach such as the use of buildup washoff coefficients. Under these circumstances, the event load is more important than the exact contaminant concentrations during the storm event. Furthermore, 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 in most cases (Charbeneau and Barrett 1998).

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 classes being simulated. The EMCs used in this study were obtained from the LADPW stormwater monitoring program (LADPW 2000). Part of the LADPW stormwater monitoring program is the monitoring of runoff from predominantly single land use catchments. 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 model. These EMCs were not specific to the watershed studied. The EMCs were specific to Los Angeles County and the study watershed resides in that county. Simulating stormwater quality using land use specific EMCs in SWMM produces constant concentrations from each land use during each storm event. Concentrations at the outlet of the watershed are variable because different catchments with different land uses contribute flow throughout the runoff event.

Table 3. Ballona Creek Storm Water Management Model Model Relative Error

Parameter	Relative error
Runoff volume	10.6
Total copper	49.7
Total lead	75.9
Total nickel	68.3
Total chromium	57.5

Model Calibration

Calibration is a crucial step in stormwater quality modeling. Calibration of the Ballona Creek SWMM model was performed using data from a mass emission monitoring station at the downstream end of the Ballona catchment. The Ballona Creek SWMM model was calibrated for water quality and quantity for four storms in the 1997 water year using flow and concentration data from the mass emission station. Percent imperviousness was modified globally in the model until runoff volumes and estimated total pollutant loads were comparable to observed data. Table 3 shows the results of the model calibration. The cumulative relative error for the simulated runoff volumes in the four calibration storms was 10% indicating good agreement with observed data. The performance of the model was less for metals loads. All constituents simulated had a cumulative relative error for mass loading of 50–75%.

Results

The DWF in Ballona Creek ranged from 8×10^{-2} to $2\ m^3/s$, while the DWF in Sepulveda Channel and Centinela Creek ranged from 2×10^{-2} to $5.5\times10^{-1}\ m^3/s$ and from 3×10^{-3} to $8\times10^{-2}\ m^3/s$, respectively. Fig. 3 compares the annual DWF and WWF volumes with the annual precipitation volume for the Ballona Catchment for the 1991–1996 water years. The DWF volume was consistent at levels greater than $10^7\ m^3$ for every year of the study except the 1991 water year. Because of its dependence on the stochastic rainfall process, WWF volume was highly variable from year to year and showed no general trend. The WWF volume ranged from a low of $3.6\times10^7\ m^3$ to a high of $10.6\times10^7\ m^3$. The DWF accounted for 9–25% of the total annual discharge from the Ballona catchment in this period. 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).

While the DWF produced less than 25% of the average annual

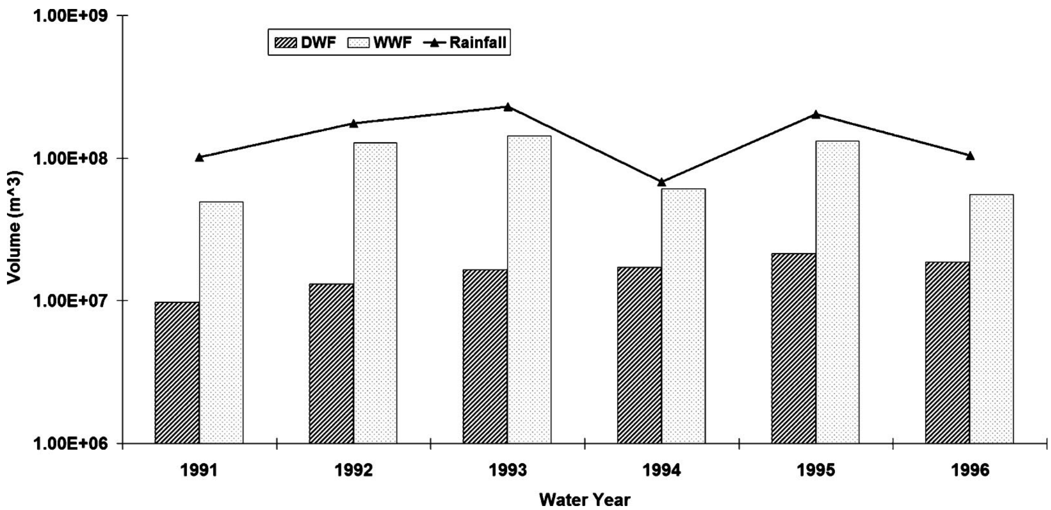

Fig. 3. Dry-weather flow and wet-weather flow volumes (m^3) 1991–1996

runoff volume, it produced a higher proportion of the average annual pollutant loading. Table 4 details the annual trace metal pollutant load from DWF and WWF in the Ballona Creek watershed. WWF still produces the majority of the average annual pollutant load of TSS, Cu, Pb, and Ni, but DWF contributes 19–44% of the annual total metals load of those constituents. The average DWF contribution to the annual average load of Cr was greater than the WWF contribution. Although WWF accounts for between 41 and 81% of the average annual load for each metal, precipitation occurs on average only 37 days/year. Therefore, the majority of the annual load is being discharged from Ballona Creek during relatively short time periods occurring during the wet season.

Although WWF is the dominant source annually for most metals, DWF is responsible for the majority of the pollutant load during the dry season. In this study, the definition for the dry season, April 1–September 30, is same as that used by LADPW (Los Angeles Department of Public Works 1998). Fig. 4 shows the percentage of the total annual load that is contributed by DWF and WWF seasonal pollutant loads. Greater than 70% of the pollutant loading of all metals from this watershed occurs in the wet season. The WWF is responsible for the majority of the pollutant load during that season. During the dry season, DWF accounts for 60–90% of the load of the metals. The seasonal results were expected because precipitation totals are very low during the dry season and high during the wet season. The DWF load for each pollutant was nearly the same during the dry season as it was during the wet season suggesting that DWF is not influenced by season. This is not an unexpected result in the Mediterranean climate of Southern California where outdoor water use may not change considerably throughout the year.

The contribution from DWF relative to WWF becomes more significant when the individual catchments within the watershed are considered. Fig. 5 shows the WWF and DWF loads for the Ballona, Sepulveda, and Centinela Catchments as a percentage of the average annual load for the entire Ballona Creek watershed. The predominant source of each contaminant, except Cr, is still WWF from Ballona Creek, but DWF from Ballona Creek is largest source of Cr and the second largest source of Pb and Ni. DWF from Ballona Creek is also a greater source of all metals than Centinela Creek WWF, but is a lower source than Sepulveda Channel WWF for Cu. DWF from the Ballona and Sepulveda catchments are minimal sources of TSS. Nearly 95% of the TSS annual average load is from Ballona catchment WWF. Overall, the results from the analysis define the importance of the Ballona Catchment in the annual pollutant load discharge from the Ballona Creek watershed.

Discussion

This study evaluated DWF and WWF heavy metal loads from the Ballona Creek watershed for the 1991–1996 water years. The goal

Table 4. Average Annual Total Trace Metal Pollutant Load in Dry-Weather Flow (DWF) and Wet-Weather Flow (WWF) from Ballona Creek Watershed

Contaminant	Average annual DWF load (kg)	Average annual WWF load (kg)	Percent of annual load from DWF
TSS	91,940	4,944,380	2
Chromium	220	190	54
Copper	250	1,060	19
Lead	150	300	33
Nickel	160	200	44

Note: TSS=total suspended solids.

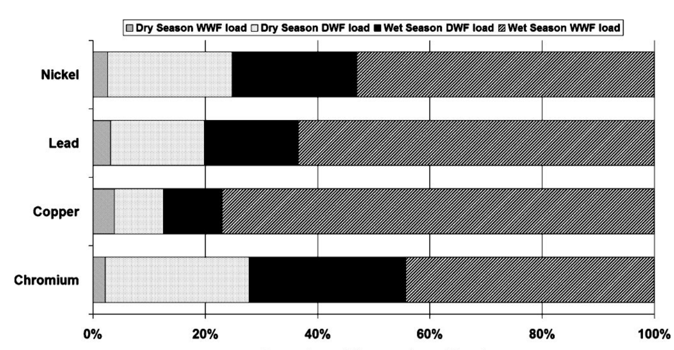

Fig. 4. Dry-Weather Flow and Wet-Weather Flow seasonal pollutant load contributions

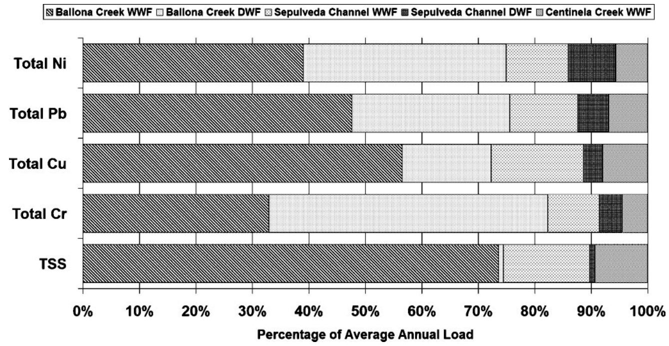

Fig. 5. Dry-Weather Flow and Wet-Weather Flow catchment pollutant load contributions

was to compare the relative contributions of TSS and the total metal loads of Cu, Pb, Ni, and Cr in DWF and WWF from the watershed and its catchments. The WWF was found to be the largest nonpoint source of metals from the Ballona Creek Watershed. The DWF was also an important source, contributing 9–25% of the flow volume and 19–54% of the annual pollutant load.

The ultimate toxic effect of DWF and WWF pollutant loads depends on the physico-chemical properties of the receiving water and the constituents of concern. The Ballona Creek Watershed has two potential receiving water systems: (1) the Ballona Creek Estuary, and (2) Santa Monica Bay. This research does not address the receiving water impacts on either of these systems, but assesses the relative pollutant contribution from DWF and WWF in each catchment. This assessment therefore provides baseline information for effective decisions on reducing the effects of urban runoff pollutant loads to these receiving waters. Both DWF and WWF eventually reach Santa Monica Bay and the toxic effect within that waterbody of the contaminant load in each flow type should be considered. Bay et al. (1999) found stormwater plumes discharged from Ballona Creek into Santa Monica Bay caused toxicity in tested species. Lau et al. (1994) came to a similar conclusion for DWF samples from Ballona Creek, but the effect of DWF following discharge to and dilution in the Ballona Creek Estuary or Santa Monica Bay is unknown. Due to the channelization of the Ballona Creek Estuary and the high flowrates of WWF, it is unlikely that the full toxic effect of the WWF pollutant load is exhibited in that system. Average base flow from the Ballona Creek catchment was approximately $41\times10^{-2}\ m^3/s$ from 1991 to 1996. During wet weather, the flow in the channel drastically increases with flows greater than $283\ m^3/s$ having been recorded at the F38C-R gauging station.

While the tidal nature of this system was noted by Suffet et al. (1997) to retain the WWF at high tide, the system also was noted to flush the visible contaminants (i.e., trash) during the ensuing low tide. The low flowrates within DWF suggest that much of its contaminant load may remain within the Ballona Creek Estuary for a significant period of time. This is potentially of concern as the Ballona Creek Estuary will be used as the source water for the Ballona Creek wetlands, a wetland restoration effort in that watershed. To assess the ultimate receiving water impacts of DWF and WWF a further understanding of the chemical properties of each receiving water and their interactions with both DWF and WWF loads is necessary.

The results of this study indicate that in the Ballona Creek Watershed the effects of pollutant loading from dry weather nuisance flow may be significant. This phenomenon may be true in other urbanized Southern California watersheds where the annual rainfall is low. The significance of DWF as shown by the results indicates the need to consider its control or treatment. Integrated DWF and WWF management would likely be the most cost-effective plan, but the infrequent and unpredictable nature of the WWF presents management difficulties. DWF on the other hand is a fairly consistent flow in quantity and quality in this watershed, which would permit the easier development and implementation of management practices. 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 (*Civil Engineering* 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). Only considering the results of this study (neglecting feasibility studies, cost/benefit analyses, and environmental impact assessments) the treatment of DWF in Ballona Creek would seem to be a logical option to protect water quality in the Ballona Creek Estuary and Santa Monica Bay.

Conclusion

In this study, we compared the relative pollutant contributions of the trace metals copper, lead, nickel, and chromium in urban DWF and WWF from a Los Angeles, Calif. watershed using historical flow data, water quality monitoring data, and computer modeling. The results indicate DWF contributes a considerable amount of flow and pollutants. The DWF accounted for up to 25% of the total annual Ballona Creek flow volume in the years studied and a considerable portion of the annual contaminant load for the metals studied. In the dry season when precipitation is infrequent, the simulations indicate DWF accounts for an even larger fraction of the pollutant load. Therefore, this research suggests DWF controls may be an important part of nonpoint source pollution mitigation plans for urban stormwater drainage systems in Southern California.

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