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Rainfall interception of three trees in Oakland, California

Qingfu Xiao · E. Gregory McPherson

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Abstract A rainfall interception study was conducted in Oakland, California to determine the partitioning of rainfall and the chemical composition of precipitation, throughfall, and stemflow. Rainfall interception measurements were conducted on a gingko (*Ginkgo biloba*) (13.5 m tall deciduous tree), sweet gum (*Liquidambar styraciflua*) (8.8 m tall deciduous), and lemon tree (*Citrus limon*) (2.9 m tall broadleaf evergreen). The lemon, ginkgo, and sweet gum intercepted 27.0%, 25.2% and 14.3% of gross precipitation, respectively. The lemon tree was most effective because it retained its foliage year-round, storing more winter rainfall than the leafless ginkgo and sweet gum trees. Stemflow was more important for the leafless sweet gum. Because of its excurrent growth habit and smooth bark, 4.1% of annual rainfall flowed to the ground as stemflow, compared to less than 2.1% for the lemon and 1.0% for the ginkgo. Water samples were collected from throughfall, stemflow, and a nearby control site to measure concentrations of nutrients and heavy metals. Compared to the control, samples from under trees had higher concentrations of nutrients and metals (e.g., N, P, K, Zn and Cr), indicating that atmospheric deposition to tree crowns was a major source of pollutants. Nutrient and metal concentrations were highest in gingko tree's throughfall. Its rough stem surfaces and dense branching pattern appeared to trap more pollutions than the other two trees.

Keywords Rainfall interception · Nutrients and metals concentration · Pollutants distribution · Urban forest · Urban runoff

Introduction

Sustainable economic development and ecosystem health are linked to the quantity and quality of a region's water resources. In the San Francisco Bay-Delta region, pollutants in

Q. Xiao (✉)
Hydrologic Sciences Program, Department of Land, Air, and Water Resources, University of California, 1731 Research Park Dr., Davis, CA 95618, USA
e-mail: qxiao@ucdavis.edu

E. G. McPherson
USDA Forest Service, Pacific Southwest Research Station, Urban Ecosystems & Social Dynamics Program, Davis, CA 95618, USA

urban runoff have significantly degraded local ecosystems (Beck and Sanudo-Wilhelmy 2007; Davis et al. 2007; Schoellhamer et al. 2007; Thompson et al. 2000). For example, in San Francisco Bay, poor water quality due to excessive discharge of pollutants has caused environmental problems. Elevated dissolved copper concentrations have generated concern for copper toxicity in this system as total dissolved copper concentrations approach and sometimes exceed state and national water quality guidelines (Buck et al. 2007), and aquatic products have been unsafe for human consumption due to high concentrations of heavy metals (Davis et al. 2008). Managing water resources to provide beneficial uses and restore the ecological health of the Bay-Delta ecosystem has become an important task for many government agencies, non-profit organizations, and other public agencies (Gerlak and Heikkila 2006; Innes et al. 2007; Jacobs et al. 2003).

Trees that collectively comprise the urban forest reduce stormwater runoff by intercepting 15% to 27% of annual rainfall (Crockford and Richardson 2000; Xiao and McPherson 2002; Xiao et al. 1998). Rainfall entering the tree crown can be partitioned into three pathways: throughfall, stemflow, and interception (or interception loss) (Ward and Robinson 1990). Throughfall accounts for precipitation that passes directly through the canopy and water that drips from leaves and branches. Stemflow is the portion of precipitation intercepted by the canopy that flows down the stems, branches, and bole to the ground. Interception accounts for the portion of rainfall that is intercepted by the crown and never reaches the ground surface, thereby not contributing to surface runoff. Evaporation of intercepted rainfall influences the distribution of water and energy within the urban ecosystem.

Factors that influence rainfall interception by tree crowns are 1) characteristics and magnitude of rainfall events; 2) tree species and architecture; and 3) meteorological factors (Staelens et al. 2007; Xiao et al. 2000a; Xiao et al. 2000b). Rainfall intensity, duration, and temporal distribution determine the amount of rainwater that drives the interception process. Tree crown architecture, leaf and stem surface areas, and foliation period influence the amount and timing of flow within the crown. Temperature, relative humidity, net radiation, and wind speed control the rate water is removed from tree surface storage. These factors vary with geographic location. For example, the leaf surface areas of urban trees depends on species, location, and maintenance practices (Peper and McPherson 2003).

The effects of rainfall interception on both runoff quality and quantity have been reported for rainforests and rural forests for various tree types and species (Chang and Matzner 2000; Engelits et al. 1984; Jetten 1996; Muoghalu and Johnson 2000; Staelens et al. 2008; Takagi et al. 1997; Xiao et al. 2000b). However, few studies have been conducted in urban settings that measure the partitioning of rainfall and the chemical composition of throughfall and stemflow (Dochinger 1980; Takagi et al. 1997). Understanding how these processes vary with different types of trees will aid efforts to increase tree canopy cover and reduce stormwater runoff in urban watersheds. Thus, the objectives of this study were to 1) quantify interception by three different tree species, 2) partition rainfall into interception, throughfall and stemflow for summer and winter events, 3) quantify and compare fluxes of nutrients and metals in throughfall and stemflow for the evergreen and deciduous trees.

Methods

Study site

All trees were located in a typical single family residential property at 821 28th street in Oakland, California (122°16′28″W, 37°13′05″N). Oakland is located on the eastern edge of the San Francisco Bay and has a Mediterranean climate that is temperate and seasonally arid. The average annual precipitation is 582.7 mm and 83% of the annual precipitation falls between November and March (National Climatic Data 2002). Temperatures during summer are cooler than most nearby inland cities because of Oakland's location on the San Francisco Bay and directly across from the Golden Gate Bridge, through which cooling maritime fog flows.

The residential study site contained a house located near the middle the property (Fig. 1). A mini-weather station was installed at the southeast corner of the property and data were recorded every 5 to 30 min by a datalogger (CR10, Campbell Scientific, Inc.). The three study trees were selected because they were the largest trees located on the eastern side of the property and their crowns did not overlap with other nearby trees. The two largest trees were a deciduous ginkgo (*Ginkgo biloba*, 13.5 m tall deciduous tree) and sweet gum (*Liquidambar styraciflua*, 8.8 m tall deciduous). The third tree was a small broadleaf evergreen lemon (*Citrus limon*, 2.9 m tall broadleaf evergreen) tree. Tree crown projection

Fig. 1 Study site. The aerial image shows the property's boundary line, house, trees marked with white dots (from top are ginkgo, sweet gum, and lemon) and control site marked with a star (weather station). Each tree and the weather station are shown as separate images

area (CPA), the area within the drip line, was measured with high resolution aerial imagery (data source: USGS High Resolution Orthoimagery, 2005) and verified with field measurements of average crown diameters. Leaf surface area, stem surface areas, and leaf area index (LAI), or leaf area per unit CPA, were estimated based on previously established size relationships for these trees in the San Francisco Bay region (Maco et al. 2005; Maco et al. 2003; Peper and McPherson 2003; Peper et al. 2001). Size and other features of these three trees are listed in Table 1.

Field measurements

The control site was 13.4 m southwest of the house and 3.7 m from the lemon tree. It consisted of an onsite mini-weather station that measured air temperature, relative humidity (HMP45C Temperature and relative Humidity Probe, Campbell Scientific, Inc.), wind speed and direction (03001 Wind Sentry, Campbell Scientific, Inc.), and precipitation (TE525 Tipping Bucket Rain Gage, Campbell Scientific, Inc.). Precipitation from the control site (i.e., rainwater), water dripping off the tree crowns (i.e., throughfall), and water flowing down the tree trunks (i.e., stemflow) were collected to determine their quantity and quality. Rainwater was collected in a PVC container (Schedule 40, inside diameter: 10.2 cm, height: 15.2 cm). A stainless steel mixing bowl (diameter: 40.6 cm) placed on a concrete half block (20.3 cm× 20.3 cm×20.3 cm) collected rainwater for quality analysis. Ten PVC containers were randomly located below each tree to collect throughfall. To prevent contamination of the samples by splashing soil particles, each container was set on a base that elevated the container at least 16.5 cm above the ground. The bases were built with two brick pavers and pressure-treated wood. Four metal screws attached the containers to the wood. The bases were placed in builder's sand and leveled (Stanley Magnetic Torpedo Level). All containers were cleaned with tap water and dried with a clean cotton towel between storm events. Containers were placed (or relocated) according to a pre-established scheme with 25 sets of ten randomly determined locations (angle from north and distance from the tree bole) for each tree.

Table 1 Dimensions of the experimental trees

Parameters	Tree		
	Ginkgo (*Ginkgo biloba*)	Sweet gum (*Liquidambar styraciflua*)	Lemon (*Citrus limon*)
Height (m)	13.5	8.8	2.9
DBH[a] (cm)	64.7	18.6	10.1
Crown diameter (m)	10.1	4.6	3.4
Crown projection area (m^2)	80.1	16.6	9.1
Crown shape	Paraboloid	Paraboloid	Paraboloid
LAI	5.2	4.7	3.0
Gap fraction	0.21(S[b]), 0.64 (W[c])	0.16 (S), 0.73 (W)	0.18 (S), 0.18 (W)
Foliation period	March 16–November 15	April 16–December 31	January 1–December 31

[a] Diameter at Breast Height (1.4 m). The lemon tree had branches below breast height, so the bole diameter was measured immediately below the first branch where there was no lateral expansion resulting from branch growth

[b] Leaf on

[c] Leaf off

Stemflow was collected directly from the tree stem using a channel fabricated from soft Tygon tubing that was split and spiralled around each tree stem. Gaps between tubing and the tree bole were sealed with 100% silicone clear sealant. One 18.9 L water container received all stemflow from the lemon tree. Two 18.9 L containers stored stemflow from the sweet gum tree. Stemflow was not collected from the ginkgo tree because it was only observed during the largest storm events (greater than 50.8 mm), probably because of the tree's rough and highly absorbent bark. The ginkgo's stemflow was calculated based on field observation and data from a previous study by the authors for a similar tree species (McPherson et al. 1999). The measurement sites were secured with fences.

Measurements were conducted during each storm event. A storm event was defined as a rainfall period separated by a dry period lasting at least 24 h (Hamilton and Rowe 1949; Xiao et al. 2000b). After each rainfall event, throughfall samples were collected and combined in one large bucket for each tree. The amount of throughfall was measured with a standard measurement device (i.e., laboratory glass graduated cylinder) and a 400 ml sample was stored in plastic water bottles (HDPE leak-resistant narrow-mouth plastic bottle, Wheaton Science Products, Millville, NJ 08332). The same procedures were used for measuring and sampling stemflow. Bottles were put in ice coolers and delivered to the Agriculture and Natural Resources (ANR) laboratory at the University of California within 48 h of collection. Extremely large (greater than 262.6 mm) and small (less than 3.8 mm) storm events were excluded from analysis because interception has little impact. During very large storms the crown becomes quickly saturated, and small storms generate little runoff (Xiao et al. 2000b). Rainfall measured at the on-site microclimate station was used to determine storm size.

Rainfall partitioning

Partitioning rainfall requires finding relations among precipitation, throughfall, stemflow, and interception. Interception can be described as the difference between gross precipitation (P) and net precipitation (P_n), where P_n consists of throughfall (TH) and stemflow (ST). At a more detailed level, interception can be partitioned into canopy surface water storage (C) and evaporation (E). Throughfall can be further separated into free throughfall (Th) and canopy drip (D).

$$C + E = P - (TH + ST) \tag{1}$$

Equation (1) can be used to solve for interception (I, or C+E) with knowledge of the gross precipitation term (P) and net precipitation term (TH and ST). Throughfall (TH) collected in the field included both free throughfall (Th) and water dripping from tree branches (D). For unit conversion, all components in equation (1) were converted into one dimension [L] via the following calculations.

$$\begin{aligned} P[L] &= P[L^3]/A_P[L^2] \\ TH[L] &= TH[L^3]/A_{TH}[L^2] \\ ST[L] &= ST[L^3]/CPA[L^2] \end{aligned} \tag{2}$$

Where [L], [L^2], and [L^3] are dimensional units for depth, area, and volume, respectively. A_P is the collection area of the rainwater container. A_{TH} is the collection area of the throughfall containers. CPA is tree crown projection area or the area within the drip line.

Rainfall interception of each tree was partitioned for each storm event, leaf-off and leaf-on seasons, and for the entire measurement period.

Laboratory analysis

The laboratory water quality analyses focused on pollutants identified as important to the quality of water in the Bay-Delta system (US-EPA 1983). Parameters measured included nutrients (i.e., total Kjehldahl nitrogen (TKN), ammonia (NH_4-N), nitrate (NO_3-N), phosphorus (P), and potassium (K)) and metals (i.e., zinc (Zn), copper (Cu), chromium (Cr), lead (Pb), iron (Fe), selenium (Se), nickel (Ni), mercury (Hg), and cadmium (Cd)). Conventional water quality properties such as pH, electrical conductivity (EC), and total dissolved solids (TDS) were measured. The majority of these water quality parameters were analyzed at the Division of Agriculture and Natural Resources (ANR) Analytical Laboratory, University of California. The ANR Analytical Laboratory performs water quality analyses for these selected chemical constituents with EPA recommended or standard analytical methods. For nutrients, the Method Detection Limits (MDL) was 0.05 mg/L except 0.1 mg/L for TKN. For metals, the MDL was 0.1 mg/L for Cu, 0.02 mg/L for Zn, 0.05 mg/L for both Ni and Pb. For Cr and Cd, the MDL was 0.005 mg/L, and 1 μg/L for Se and Hg. The pH, EC, and TDS were measured immediately after the water samples arrived at the laboratory using the Ultrameter II (ULTRAMETER II, Models 6P, Myron L Company, 2450 Impala Drive, Carlsbad, CA 92010 USA). This instrument had a measurement resolution of 0.01% of both EC and TDS and 0.1 for pH. The instrument was calibrated with NIST (National Institute of Standards and Technology) traceable Standard Solutions having specific conductivity/ppm values before each measurement. Standard statistical analytical methods (i.e., mean, minimum, and maximum concentrations, and standard deviation) were used to perform water quality data analysis.

Results and discussion

Rainfall interception

During the study period (2005–2007 rain seasons) there were 25 storm events (Fig. 2). Annual precipitation was 728.2 mm, considerably more than the long time average (582.7 mm) due to frequent storms in December that brought more than 266.0 mm of precipitation. Of these 25 events, 16 were measured in the field (446.2 mm). Nine storm events (281.9 mm) were excluded from the water quality analysis. Eight events were less

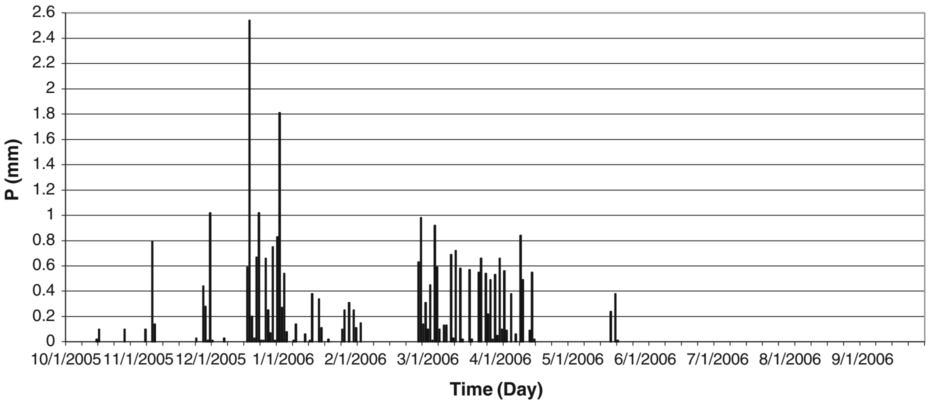

Fig. 2 Daily precipitation of 2006 water year (from Oct. 1, 2005 to Sept. 30, 2006)

than 3.8 mm each and one was a very large storm (262.6 mm) that resulted in both throughfall and stemflow containers overflowing.

Rainfall interception varied with tree species and season. On average, the lemon, ginkgo, and sweet gum intercepted 27.0%, 25.2% and 14.3% of gross precipitation, respectively (Table 2). The lemon tree, which retained its foliage year-round, intercepted relatively more rainfall than the deciduous ginkgo and sweet gum trees. The lemon had a broad, spreading

Table 2 Rainfall partitioning for three trees

Date	Rainfall (mm)	Throughfall (%)			Stemflow (%)			Interception (%)		
		La	S[a]	G[a]	L	S	G	L	S	G
10/5/2005	17.5	0.0	77.5	76.1	3.2	7.5	0.0	96.8	15.0	23.9
11/13/2005[b]	24.2	N/A	81.6	N/A	3.2	6.6	0.0	N/A	11.8	N/A
2/26/2006	7.9	0.0	79.9	0.0	3.7	6.0	0.0	96.3	14.1	100.0
3/5/2006	74.0	70.0	81.7	71.7	1.2	7.3	0.0	28.8	11.0	28.3
3/9/2006	6.7	49.1	75.9	74.1	1.8	6.7	0.0	49.1	17.4	25.9
3/12/2006	24.7	70.0	75.0	70.0	1.9	6.6	0.0	28.1	18.4	30.0
3/15/2006	86.3	51.4	80.0	71.4	1.1	5.6	2.0	47.5	14.4	26.6
Leaf-off	*241.3*	*48.4*	*79.9*	*62.3*	*1.7*	*6.5*	*0.7*	*40.2*	*13.6*	*27.0*
3/24/2006	15.5	77.3	68.0	66.7	1.7	6.8	0.0	21.0	25.2	33.3
3/27/2006	18.5	66.7	92.0	66.7	1.7	4.5	0.0	31.6	3.5	33.3
3/31/2006	15.5	77.2	74.0	71.6	4.2	6.6	0.0	18.6	19.4	28.4
4/3/2006	45.0	93.2	80.0	74.4	2.1	2.0	0.0	4.7	18.0	25.6
4/7/2006	20.4	70.3	72.4	74.2	3.9	4.6	0.0	25.8	23.0	25.8
4/11/2006	33.9	78.0	69.5	51.8	2.1	5.3	0.0	19.9	25.2	48.2
4/15/2006	32.1	48.7	64.6	62.3	1.7	5.4	0.0	49.6	30.0	37.7
5/19/2006	8.6	41.7	32.0	28.0	2.8	3.7	0.0	55.5	64.3	72.0
5/21/2006	15.4	39.6	24.0	28.0	4.9	3.0	0.0	55.5	73.0	72.0
Leaf-on	*204.9*	*70.4*	*68.6*	*61.8*	*2.5*	*4.4*	*0.0*	*27.0*	*27.0*	*38.2*
Min	6.7	0.0	24.0	0.0	1.1	2.0	0.0	4.7	3.5	0.0
Max	86.3	93.2	92.0	76.1	4.9	7.5	2.0	96.8	73.0	100.0
Median	19.5	59.1	75.5	68.4	2.1	5.8	0.0	39.6	18.2	29.2
11/4/2005 [c]	2.5	18.0	16.0	21.0	0.0	0.0	0.0	82.0	84.0	79.0
11/25/2005 [c]	0.5	18.0	16.0	63.5	0.0	0.0	0.0	82.0	84.0	36.5
12/7/2005 [c]	3.3	18.0	16.0	63.5	0.0	0.0	0.0	82.0	84.0	36.5
12/17/2005 [c]	262.6	96.2	95.6	95.4	2.0	2.0	2.0	1.8	2.4	2.6
1/6/2006 [c]	3.8	18.0	73.0	63.5	0.0	0.0	0.0	82.0	27.0	36.5
1/11/2006 [c]	2.0	18.0	73.0	63.5	0.0	0.0	0.0	82.0	27.0	36.5
1/30/2006 [c]	2.0	18.0	73.0	63.5	0.0	0.0	0.0	82.0	27.0	36.5
2/4/2006 [c]	3.6	18.0	73.0	63.5	0.0	0.0	0.0	82.0	27.0	36.5
4/9/2006[c]	1.5	18.0	16.0	21.0	0.0	0.0	0.0	82.0	84.0	79.0
Total	728.1	71.0	81.6	73.9	2.0	4.1	1.0	27.0	14.3	25.2

[a] *L* lemon (*Citrus limon*); *S* sweet gum (*Liquidambar styraciflua*); *G* ginkgo (*Ginkgo biloba*)

[b] Throughfall collection for the gingko and lemon trees failed on11/13/2005

[c] Throughfall was estimated based on gap fraction. Stemflow was estimated when observed in the field

crown covered with smooth evergreen leaves that kept rainfall from reaching underlying branch surfaces.

Rainfall partitioning

The ginkgo intercepted more rainfall than the sweet gum across almost all storm events. Stemflow was more important for the leafless ginkgo and sweet gum until they began to leaf-out during late-March and April. Their gradual increase in leaf surface area was accompanied by greater rainwater interception and reduced free throughfall.

Stemflow measured from the sweet gum was two times greater than from the evergreen lemon tree. The sweet gum had an excurrent growth habit, with a strong central leader and scaffold branches attached at angles of about 45°. Rainwater flowed down the smooth stem surfaces to the bole with very little resistance. In contrast, the ginkgo's scaffold branches were more horizontal and the stem surface was rougher and absorbent than the sweet gum's. As a result, stemflow in the ginkgo was slower and relatively little water converged at the bole. Stemflow from the ginkgo tree was only observed during the largest winter storm events (Dec. 17, 2005 and Mar. 15, 2005).

Both throughfall and stemflow were linearly related to rainfall (Fig. 3a–b). Rainfall interception, throughfall, and stemflow by the deciduous trees were influenced by seasonal variation in leaf surface area (Table 2). On average, sweet gum throughfall decreased from 79.9% during leaf-off season (from Oct. 1 to Mar. 15) to 68.6% during leaf-on season. Stemflow decreased from 6.5% during leaf-off season to 4.4% during the leaf-on season. These seasonal changes caused average interception to increase from 13.6% during the leaf-off season to 27.0% during the leaf-on season.

Partitioning of rainfall for a typical winter and summer storm event illustrates the different response by deciduous and evergreen species. A late winter storm event that started at 13:00 March 24, 2006 and ended at 18:00 of March 25, 2006 had 15.5 mm total precipitation (Fig. 4a). An early summer event occurred on May 21, 2006 and had 15.4 mm total precipitation that came in two concentrated periods. The first period (6.2 mm) started at 13:00 and ended at 19:00 on May 21 and the second period (8.6 mm) started at 13:00 and ended at 24:00 on May 23. The ginkgo and sweet gum were leafing-out at this time, but had not reached full foliation. Rainfall interception for the ginkgo, sweet gum, and lemon trees during the winter storm was 31.3%, 25.5%, 21.0%, respectively and 70.0%, 73.0%, and 55.5%, respectively for the early summer storm. Unlike most winter storms, the summer storm came after a long dry period and contained a 20-hour drying period. Thus, there was no antecedent surface moisture storage on leaf and stem surfaces, resulting in high surface storage potential.

The percentage of rainfall partitioned as interception more than doubled from winter to summer events across species. Although this result was expected for the two deciduous species, it was surprising that the evergreen lemon exhibited this seasonal trend. This finding may result from low antecedent surface moisture storage and increased LAI for both deciduous trees. The percentage throughfall was affected by LAI. The partitioned data confirm this, with throughfall percentages for the summer event of 28.0%, 24.0%, 39.6% respectively for the ginkgo, sweet gum and lemon. Lemon had the highest throughfall percentage during the summer event because it had the lowest LAI.

The percentage of total rainfall intercepted by these three trees was similar to results reported for other open-growing trees. Annual interception rates averaged 15% for a pear tree (*Pyrus calleryana* 'Bradford') and 27% for an oak tree (*Quercus suber*) in Davis, California (Xiao et al. 2000b) and 21% for single beech tree (*Fagus sylvatica* L.) in Ghent,

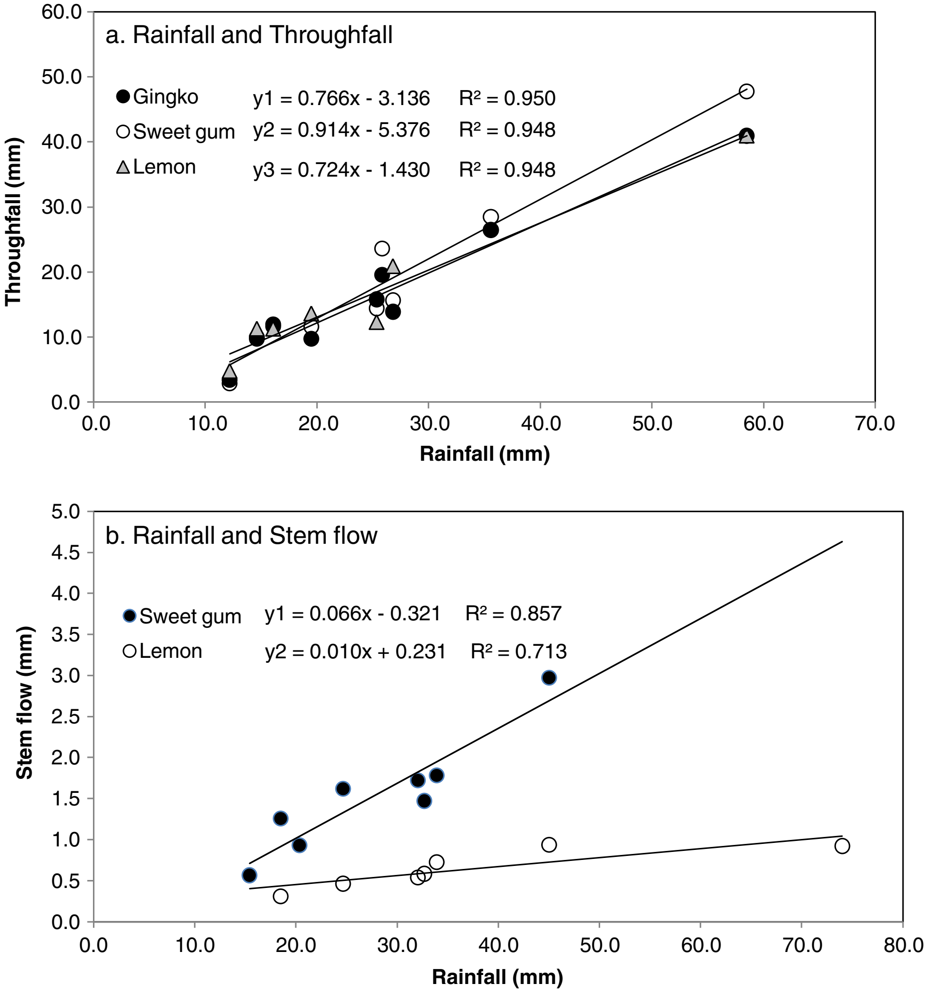

Fig. 3 Scatter plot of rainfall, throughfall (TH), and stem flow (ST). The x in the regression equations represents rainfall. **a** shows the relationship between rainfall and throughfall. y1, y2, and y3 represent throughfall for the gingko, sweet gum, and lemon trees, respectively. **b** shows the relationship between rainfall and stem flow. y1 and y2 represent stemflow for the sweet gum and the lemon trees

Belgium (Guevara-Escobar et al. 2007; Staelens et al. 2007). Interception measured during July and August for an evergreen lemon tree in Queretaro City, Mexico was 27.0%, but evaporation rates were very high at this time (Guevara-Escobar et al. 2007).

The sweet gum tree had the lowest interception rate among the three trees. Most water samples collected from the sweet gum were during the leaf-off season, when the canopy surface water storage capacity was low. During winter events the sweet gum's stemflow was two times greater (in percentage) than stemflow for the lemon and ginkgo trees. The sweet gum's branch architecture and smooth stem surfaces readily channeled flow to the bole and then the ground. The lemon's stemflow was relatively low during winter because foliage effectively intercepted rainfall and the arching branches directed stemflow outward to the dripline.

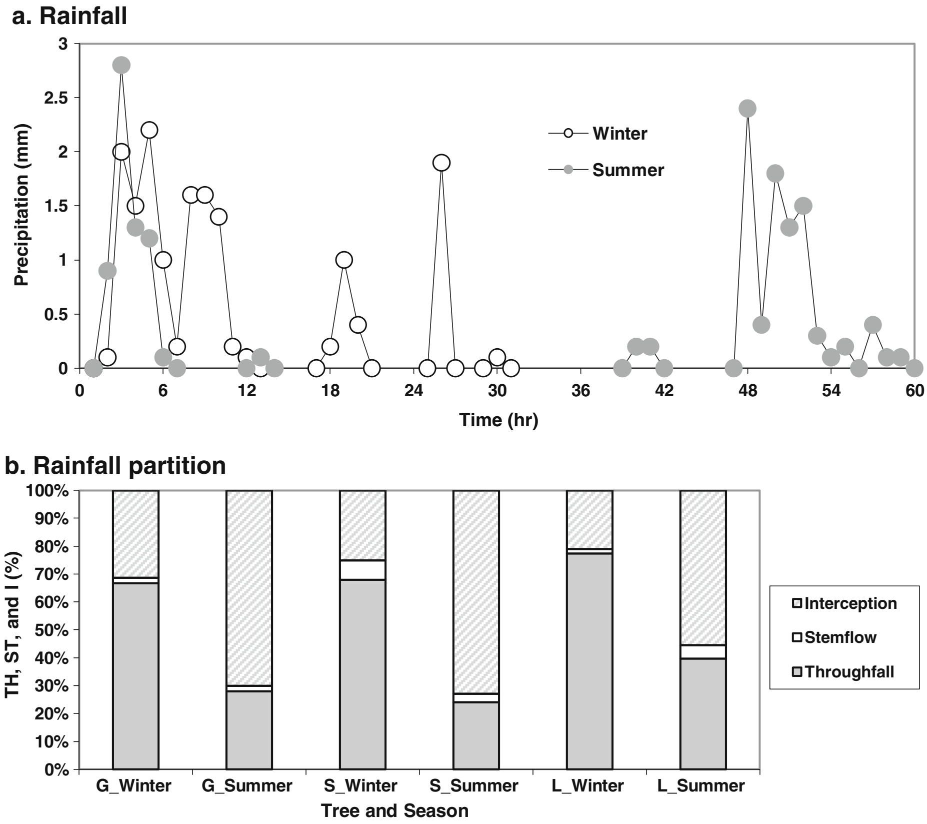

Fig. 4 Rainfall partitioning for a winter and a summer storm event. **a** Temporal distribution and depth of rainfall for the two rainfall events. **b** Y-axis shows the percentage of total rainfall partitioned into throughfall (TH), stemflow (ST) and interception (I). X-axis contains data for the ginkgo (G), sweet gum (S) and lemon (L)

Chemical composition of rainfall interception

The pH value of rainwater collected on-site was 6.9, higher than pH~5.6 reported for rainwater in other regions (Abas et al. 1992; Muoghalu and Johnson 2000) (Table 3). Oakland's rainfall is less acidic because of its proximity to the Pacific Ocean, compared to rainfall from clouds that have traveled longer distances through more polluted air, which results in increased carbonic acid content.

The mean pH values for throughfall and stemflow were lower than the pH values for rainfall collected on-site, reflecting the acidic nature of pollutants captured by tree crowns. Stemflow from the sweet gum tree had the lowest mean pH value of 6.2 (Table 3). Decayed organic matter (e.g., tree bark) on the tree surface contributed to the stemflow water quality degradation. The lowest recorded pH value (5.6) was stemflow from the lemon tree. The 5.6 value is similar to the street tree stemflow pH found in the coastal city of Tenjin, Japan (Takagi et al. 1997).

Throughfall samples collected from the lemon tree had the lowest average EC value (21.7 mS/cm (milliSiemens per centimeter)) while the EC for sweet gum throughfall was 42.8 mS/cm. Similarly, the mean EC value of stemflow measured from the sweet gum was

Table 3 pH, conductivity, and TDS of precipitation, throughfall, and stemflow

		Throughfall			Stemflow		Rainwater
		Ginkgo	Sweet gum	Lemon	Sweet gum	Lemon	
pH	Mean	6.65	6.50	6.41	6.17	6.48	6.90
	Min	6.20	6.18	6.10	6.06	5.62	6.23
	Max	6.94	6.79	6.62	6.37	7.48	7.48
	Standard Deviation	0.28	0.19	0.19	0.11	0.52	0.55
EC (μS/cm)	Mean	40.58	42.81	21.68	69.88	25.84	12.21
	Min	3.72	27.20	15.18	24.30	13.52	0.87
	Max	99.21	65.29	30.27	112.72	41.88	19.10
	Standard Deviation	37.15	17.90	5.66	31.41	10.78	7.05
TDS (ppm)	Mean	40.23	29.78	13.86	44.75	18.59	8.90
	Min	23.66	18.03	9.40	16.94	11.11	5.01
	Max	65.14	44.57	19.45	69.60	27.09	13.74
	Standard Deviation	13.74	11.78	4.10	18.55	6.00	3.66

more than two times higher than the lemon tree value (Table 3). The dense, umbrella-shaped crown of the evergreen lemon tree reduced penetration and adherence of airborne pollutants to inner branch surfaces.

TDS measured in throughfall and stemflow followed the same pattern as EC. The lowest TDS (9.4 ppm) was observed in throughfall of lemon tree, while the highest TDS (69.6 ppm) was measured in stemflow of the sweet gum. Open field rainwater samples had low EC (12.21 mS/cm) and TDS (8.9 ppm). Both EC and TDS were higher in stemflow than in throughfall. This indicated that the chemistry of incident precipitation was modified as the rain drops passed through the canopy. Water flow along the stems, branches, and bole collected chemicals that were deposited from the atmosphere or decaying tree parts. EC and TDS were positively related ($TDS=0.6204EC+1.5971$, $R^2=0.9855$, $n=42$). A similar linear relationship between EC and TDS was observed in surface runoff (Udeigwe et al. 2007).

Nutrients

Nutrient concentrations of rainwater measured on-site were lower than throughfall and stemflow, indicating that nutrients were added as rainfall passed through the crown (Table 4). Foliar and woody crown surfaces intercepted these chemical constituents from atmospheric deposition. Canopy leaching was the major sources of these chemical constituents. Similar results were observed in deciduous and coniferous forests of the Georgia Piedmont (Cappellato and Peters 1995). Throughfall from the ginkgo tree had the highest nitrogen and potassium concentrations while the highest phosphorus concentrations were found in throughfall samples from the sweet gum tree. In general, the nutrients concentration of throughfall from the evergreen lemon tree was lowest. Sweet gum stemflow consistently contained higher nutrient concentrations than stemflow from the lemon tree. The amount of stemflow and its total pollutant content was less than throughfall. However, the impact of stemflow on the quality of water resources may be as important as throughfall (Tanaka et al. 1996; Taniguchi et al. 1996). Stemflow is a point

Table 4 Mean nutrients concentration (mg/L) in throughfall, stemflow, and rainwater

Chemical Constituents	Throughfall			Stemflow		Rainwater
	Ginkgo	Lemon	Sweet gum	Lemon	Sweet gum	
TKN	7.33	2.69	2.81	1.44	2.90	1.72
NH_4-N	0.93	0.63	0.56	0.57	1.30	0.53
NO_3-N	0.72	0.20	0.20	0.23	0.75	0.17
P_s[a]	1.95	0.27	3.35	0.10	1.68	0.14
P	2.48	0.53	3.29	0.16	1.76	0.35
K_s	26.66	5.75	12.91	1.11	10.65	0.88
K	28.02	5.84	13.34	1.29	11.24	1.14

[a] *_s* stands for soluble

source pollutant that collects on branch surfaces and drains via the bole to the ground. In contrast, throughfall is widely distributed under the crown. Nutrient constituents were linearly related to EC (Table 5). All constituents below MDL were excluded from this analysis.

Metals

Based on the laboratory analysis of the water samples for the 16 rainfall events, the concentrations of Zn, Cu, Cr, and Pb were above the laboratory's MDL (Table 6). The concentrations of remaining metals (i.e., Fe, Se, Ni, Cd, and Hg) were below the laboratory's MDL. Metal concentrations were below the MDL for most rain events. Zn was found in throughfall and stemflow samples collected from each tree and on-site rainwater samples. Concentrations of Zn and soluble Zn in sweet gum throughfall were higher than the lemon tree's. The rough surfaces of the sweet gum were more effectively trap atmospheric deposition. Cr was found in all samples with little change in concentration level. In general, Cr pollutant sources are emitted from local area sources, especially automobile emissions and parts wear-off. The study site is surrounded by an interstate freeway network. Pb was not detected in the rainwater samples but was found in throughfall from three trees and stemflow from the lemon tree. Pb detected in these samples were from atmospheric deposition, local housekeeping, landscape practices, and dust from industrial

Table 5 Relationship of nutrient constituents and EC

Nutrient constituents	Slope	Intercept	R-Squared	Number of samples
TKN	0.0263	0.5972	0.591	43
NH_4-N	0.0156	−0.0281	0.5252	42
NO_3-N	0.0055	0.0475	0.5326	36
P_s	0.0239	−0.2723	0.6846	11
P	0.0224	−0.145	0.5715	13
K_s	0.1137	−0.7042	0.7769	16
K	0.1163	−0.3667	0.7659	21

Table 6 Mean metal concentration in throughfall, stemflow, and rainwater

Chemical Constituents	Throughfall						Stemflow				Rainwater	
	Ginkgo		Sweet gum		Lemon		Sweet gum		Lemon			
	C[b]	N[c]	C	N	C	N	C	N	C	N	C	N
Zn	1.18	6	0.34	5	0.33	2	0.30	3	0.25	2	0.20	1
Zn_s[a]	1.10	3	0.17	3	0.11	3	0.17	3	0.15	1	0.12	1
Cu	0.30	1	–	–	–	–	–	–	–	–	–	–
Cu_s	0.30	1	–	–	–	–	–	–	–	–	–	–
Cr	0.02	3	0.01	1	0.02	2	0.02	1	0.03	2	0.01	2
Pb	0.17	3	0.15	2	0.20	1	–	–	0.30	1	–	–

All chemical constituents were measured in mg/L

[a] *_s* stands for soluble

[b] concentration

[c] number of samples had the concentration above the laboratory detect limits

activities as indicated in the State of California's Municipal Handbook (Camp et al. 1993). Hg, a major water quality concern in the Bay, was not found at concentrations above the laboratory's MDL (1.0 ug/L).

Conclusion

Although trees intercept rainfall thereby reducing stormwater runoff, they also capture and concentrate atmospheric pollutants in stemflow and throughfall. Interception effectiveness was related to the seasonal nature of rainfall and foliation. Although the evergreen lemon had the lowest LAI, it was still more effective than the deciduous ginkgo and sweet gum because it was in-leaf during the most of the measured storm events. Large, evergreen trees have higher potential for reducing stormwater runoff than smaller deciduous trees in Mediterannean climates such as this. The ginkgo was next most effective because of its semi-horizontal branching pattern and rough, absorbent bark. The sweet gum's more vertical branching pattern and smoother stem surfaces enhanced winter stemflow.

Higher concentrations of nutrients and metals in both stemflow and throughfall than in rainwater indicate that the tree crowns capture, filter and store atmospheric pollutants. The lemon tree had the lowest concentration of almost all the elements studied. The concentrations of chemical constituents varied with time and among tree species, indicating that trees in urban setting are interactively affecting hydrological processes by changing water and chemical fluxes.

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