Urban Ecosystems, 6: 291–302, 2002

Rainfall interception by Santa Monica's municipal urban forest

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Received June 23, 2003; Revised September 18, 2003; Accepted September 30, 2003

Abstract. Effects of urban forests on rainfall interception and runoff reduction have been conceptualized, but not well quantified. In this study rainfall interception by street and park trees in Santa Monica, California is simulated. A mass and energy balance rainfall interception model is used to simulate rainfall interception processes (e.g., gross precipitation, free throughfall, canopy drip, stemflow, and evaporation). Annual rainfall interception by the 29,299 street and park trees was 193,168 m^3 (6.6 m^3/tree), or 1.6% of total precipitation. The annual value of avoided stormwater treatment and flood control costs associated with reduced runoff was $110,890 ($3.60/tree). Interception rate varied with tree species and sizes. Rainfall interception ranged from 15.3% (0.8 m^3/tree) for a small *Jacaranda mimosifolia* (3.5 cm diameter at breast height) to 66.5% (20.8 m^3/tree) for a mature *Tristania conferta* (38.1 cm). In a 25-year storm, interception by all street and park trees was 12,139.5 m^3 (0.4%), each tree yielding $0.60 (0.4 m^3/tree) in avoided flood control costs. Rainfall interception varied seasonally, averaging 14.8% during a 21.7 mm winter storm and 79.5% during a 20.3 mm summer storm for a large, deciduous *Platanus acerifolia* tree. Effects of differences in temporal precipitation patterns, tree population traits, and pruning practices on interception in Santa Monica, Modesto, and Sacramento, California are described.

Keywords: urban forest, rainfall interception, evaporation, urban runoff reduction

Introduction

Tree rainfall interception plays an important role in the urban ecosystem. It affects all hydrologic processes as well as the spatial and temporal redistribution of moisture. Rainfall envelops the tree crown surface, and some raindrops directly pass through gaps between leaves and stems, plummeting to the ground as free throughfall. Rainwater intercepted on tree leaves and branches is temporarily stored on leaf and bark surfaces, eventually dripping off the surfaces to the ground as throughfall, or flowing down the trunk to the ground as stemflow, or evaporating into the atmosphere. In the urban ecosystem, canopy rainfall interception changes the urban runoff process by reducing the flow rate and shifting the runoff concentration time via temporal water storage on the canopy surface (Sanders, 1986). A decrease in storm runoff volume reduces flooding hazard, surface pollutant wash-off, and pollutant loading of the runoff. Urban runoff reduction ultimately reduces expenses

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for urban runoff control and pollutant treatment. Ways that urban forests influence urban hydrology have been conceptualized, but few studies have quantified the processes involved and resulting benefits. Studies have been conducted using estimates of vegetation coverage from satellite remote sensing (American Forests, 1996). In the dense urban fabric, typical of cities in California, remote sensing data may lack the resolution needed to distinguish important differences, such as between evergreen and deciduous species (Hung and Ridd, 2002). Furthermore, with leaf-on imagery it is difficult to characterize land surface cover underneath the tree canopy, and with leaf-off imagery it is difficult to accurately determine the amount of deciduous canopy. Rainfall interception of urban forest trees has been studied at the single-tree level in an effort to improve understanding of rainfall interception processes (Xiao *et al.*, 2000a, 2000b).

The rainfall interception capacity of the urban forest is strongly influenced by forest structure (e.g., species, dimensions, and stocking levels), tree architecture (e.g., foliation period, leaf and stem surface areas, gap fraction, surface detention storage capacity), and meteorological factors (e.g., amount, duration, intensity, frequency of events, evaporation rates) (Xiao *et al.*, 2000b). Street and park trees are usually open grown and isolated. Their relatively large crown areas and leaf surface areas provide large storage space for rainwater. During rain events each tree functions like a mini-reservoir, controlling runoff at the source. Rainfall interception by the entire urban forest can be estimated through linear theory by summing the contributions of each individual tree.

This study uses computer simulation to quantify rainfall interception by public trees in Santa Monica, California. The objectives of this study are to quantify:

- annual rainfall interception and its economic value,
- rainfall interception for a 25-year rainfall event,
- interception for winter and summer storms,
- and effects of tree-related factors, rainfall patterns, and pruning practices on annual rainfall interception.

Method

A rainfall interception study using two open grown trees found that the rain shadow caused by adjacent trees and heat storage inside the tree crowns did not influence interception and evaporation processes (Xiao *et al.*, 2000b). Street and park trees are usually isolated and open grown. Thus, total rainfall interception of these trees can be determined by a linear calculation that sums the contribution of each tree. In this study, a single-tree interception model uses tree structure and meteorological data to simulate the rainfall interception of each tree at annual, seasonal, and storm levels.

Study site

The city of Santa Monica (latitude: N34°02′00”, longitude: W118°29′00”) is located along the southern coast of California within the greater Los Angeles metropolitan area. The microclimate gradient over the study area is slight because of little variation in topography and the coastal climate. Longtime average annual precipitation is 569.5 mm. The dominant land use over the 21.8 km^2 study area is residential (66.0%). Commercial, industrial, and park land uses account for 15.9%, 7.0%, and 2.6%, respectively. The remaining 8.5% of land has other uses. Santa Monica was selected for the study because of its extensive public tree inventory and detailed information on its tree and storm runoff programs.

Rainfall interception model

A single-tree rainfall interception model (Xiao *et al.*, 1998) was used to estimate rainfall interception by different tree species at different growth stages. The interception model accounts for rainfall intercepted by the tree leaf and stem surfaces. Tree surface water storage, throughfall, stem flow, and evaporation were simulated at 1-hour time intervals. The model requires tree architecture (e.g., dimension and leaf surface area) and meteorological (e.g., precipitation, air temperature, relative humidity, wind speed, and solar radiation) data as input parameters.

Based on continuity, tree surface water storage (C) changing with time (t) is the difference among gross precipitation (p), free throughfall (th), stemflow (st), canopy drip (d), and evaporation (e). Mathematically, this can be written as

$$\frac{dC}{dt} = p - th - st - d - e \tag{1}$$

where th and st are proportional to gross precipitation by the gap fraction and the stemflow diversion coefficient.

Canopy drip d occurs when surface water storage exceeds saturation storage. It is described as an exponential function of canopy storage and saturation storage capacity (S). That concept can be expressed by the formula

$$d = d_0 e^{b(c-s)} \tag{2}$$

where d_0 is the minimum drainage rate, which is the drip rate when C equals S, and b is a dimensionless parameter.

Evaporation occurs at its potential rate when the surface is saturated. Otherwise evaporation is proportional to surface storage. The potential evaporation rate is estimated based on the well-known modified Penman formula

$$E_p = \frac{\Delta}{\Delta + \gamma} Q_{ne} + \frac{\gamma}{\Delta + \gamma} E_A \tag{3}$$

where Δ is the rate of increase of the temperature of the saturated water vapor pressure at air temperature, γ is the psychometric constant, Q_{ne} is net radiation, and E_A is the drying power of the air.

The Eq. (1) is explicitly solved using the finite difference method. Numerical instability errors were reduced by limiting the maximum time step. A detailed explanation and parameterization of this model was articulated by Xiao *et al.* (1998).

To estimate annual and seasonal rainfall interception, we projected the interception of each tree as the summation of evaporation from the tree surface during the time domain. Results are presented at the landscape (total interception/total study area) and tree crown (total interception/total crown projection area [area under tree dripline]) levels.

Tree data

Inventory data was limited to 29,229 public trees, of which 87% were street trees and 13% were park trees. We grouped trees by diameter at breast height (dbh) class for each species, except palms, which were grouped by height class. Six dbh classes ranged from 0 to 76.2 cm (30 in.) at 15.2 cm (6.0 in.) intervals. Trees were grouped by height into 4.6 m (15.0 ft) classes that ranged from 0 to 18.3 m (60.0 ft). The majority of trees were broadleaf evergreens (59.9%), 11.1% were conifers, and 22.6% were palms (Table 1). Broadleaf deciduous trees accounted for only 6.4% of the tree population. Hence, 93.6% were evergreens that retain their foliage during winter, when rainfall is greatest in Santa Monica.

In addition to the Santa Monica tree inventory, we drew data from an intensive field inventory and measurement campaign performed in summer 1999 to develop tree growth curves (Peper *et al.*, 2001a). Six hundred and six street and park trees were sampled, representing the 20 most abundant species. About 30 trees were sampled for each species and the samples included trees from the full range of classes. Tree dimensions (e.g., height, crown diameter, and dbh) were directly measured in the field and leaf surface areas were calculated from digital images (Peper and McPherson, 2003). Tree growth curves were statistically estimated based on field measurements for each species (Peper *et al.*, 2001a). The gap fraction of each species was determined using image processing techniques applied to field photos.

Table 1. Tree distribution by type and dbh

	Tree type (%)			
dbh (cm)	Broadleaf deciduous	Broadleaf evergreen	Conifer	Palm[a]
0–15.2	1.7	11.1	1.2	1.9
15.2–30.5	2.8	19.7	2.1	4.9
30.5–45.7	1.5	13.2	2.7	3.8
45.72–61.0	0.3	10.6	1.8	5.6
61.0–76.2	0.0	3.7	1.8	6.4
>76.2	0.0	1.7	1.5	0.0
Total	6.4	59.9	11.1	22.6

[a]Palm trees are classified by height class.
Height classes: <4.6 m, 4.6–9.1 m, 9.1–11.0 m, 11.0–12.8 m, 12.8–14.6 m, >16.5 m.

Meteorological data

To avoid bias estimation induced by annual climate change, meteorological data for a typical weather year was used for this study. The typical weather year was determined by analysis of available historical meteorological data (monthly precipitation and temperature). Meteorological data for 1996 (annual precipitation 570 mm) was selected because it approximates the long-time average (514 mm, year 1993–2002). We used data from the CIMIS (California Irrigation Management Information System) Santa Monica station (elevation: 104.0 m, latitude: N34°02′28″, longitude: W118°28′34″) because it provided hourly values for model input. Based on the rainfall depth-duration-frequency relationship for the Santa Monica area (Department of Public Works of Los Angeles County, 1991), data from a storm that occurred in early February of 1996 was selected to estimate rainfall interception for a 25-year event. In addition, data from a winter storm that began on March 12, 1996, and a summer storm that began on April 18, 1996, were used to simulate rainfall interception for two different seasons.

Interception and benefits

Rainfall interception by public trees was presented at three temporal scales: annual, 25-year flood event, and single event. By reducing stormwater runoff, rainfall interception reduces costs for controlling flooding and treating polluted runoff. The value of water quality benefits is estimated relative to the operational costs of treating sanitary wastewater. It costs approximately \$0.48 m^{-3} (\$0.00183 gal^{-1}) to treat sanitary waste (Condon and Moriarty, 1999). The estimated flood control benefits were based on the cost of controlling local flooding during a 25-year storm. In Los Angeles, approximately \$1.44 m^{-3} (\$0.0054 gal^{-1}) is spent annually for controlling local flooding caused by a potential 25-year flood event (McPherson *et al.*, 2000).

Results

Annual rainfall interception

Annual rainfall interception was 193,168 m^3 (6.6 m^3 per tree) (Table 2). Broadleaf evergreen trees were responsible for more than half (60.0%) of this interception. Broadleaf deciduous trees contributed only 3.9%, conifers contributed 23.0%, and the remaining 13.2% was contributed by palm trees. The implied value of this interception totaled \$110,890 (\$3.80/tree). The average annual per tree monetary value of avoided storm water treatment was \$3.20, while the value for avoided flood control was \$0.60. For the population, mature trees in the 46–61 cm dbh class provided the greatest benefit (28% of total interception). Interception loss was 27.3% at the crown level, but 1.6% of annual precipitation at the landscape level because the street and park tree canopy covered only 5% of the city land area. Street and park trees account for 40% of total tree cover in Santa Monica (McPherson and Simpson, 2002). Assuming remaining city tree cover has a similar structure, the total annual interception is approximately 289,752 m^3.

Table 2. Total annual rainfall interception (m^3) by tree type and dbh class

	dbh classes (cm)							
Tree type[a]	0–15.2	15.2–30.5	30.5–45.7	45.7–61.0	61.0–76.2	>76.2	Total	% Total
BDL	55.7	297.0	307.8	235.5	129.9	219.8	1,245.7	0.6
BDM	175.2	1,109.7	1,033.4	489.1	0.0	0.0	2,807.5	1.5
BDS	208.2	1,704.6	1,557.1	0.0	0.0	0.0	3,469.9	1.8
BEL	129.6	1,260.7	2,864.8	3,248.2	4,267.6	8,377.8	20,148.8	10.4
BEM	911.6	8,619.6	19,852.0	28,891.0	14,921.6	2,375.0	75,570.8	39.1
BES	1,591.5	10,775.8	5,192.5	2,059.8	418.5	207.0	20,245.2	10.5
CEL	457.3	2,617.4	6,712.8	7,393.7	13,132.2	13,541.6	43,855.0	22.7
CES	23.3	244.7	137.4	58.1	31.4	0.0	495.0	0.3
PEM	137.3	693.4	3,351.1	9,273.1	2,489.8	0.0	15,944.7	8.3
PES	54.6	977.9	1,109.6	2,035.0	5,208.8	0.0	9,385.8	4.9
Total	3,744.4	28,301.0	42,118.4	53,683.4	40,599.8	24,721.4	193,168.4	100.0
% Total	1.9	14.7	21.8	27.8	21.0	12.8	100.0	

[a]B = Broadleaf, D = Deciduous, E = Evergreen, C = Conifer, P = Palm, S = Small (<3 m tall), M = Medium (3–8 m tall), L = Large (>8 m tall).

Rainfall interception for a 25-year flood event

The 25-year flood event began at noon on February 19, 1996, and lasted 57 hours. Precipitation totaled 134.2 mm. Interception by the public trees was 7.3% at the tree crown level and 0.4% of the storm at the landscape level. Runoff reduction was 12,159 m^3 and the value of avoided flood control costs was $17,506. For this type and size of storm, each tree intercepted 0.42 m^3 of rainfall on average, and this benefit was valued at $0.60 per tree.

Rainfall interception per tree

Annual rainfall interception varied widely among species and tree size classes. Table 3 shows annual and peak event rainfall interception for six species. The first three species are broadleaf deciduous trees and the last three are broadleaf evergreen trees. Interception by deciduous trees is relatively less than for similar sized evergreens because only 22% of annual precipitation fell while deciduous trees were in full leaf. The small-sized jacaranda (*Jacaranda mimosifolia*) intercepted more rainwater than the medium-sized sweetgum (*Liquidamber styraciflua*), mainly due to the difference in foliation period. The jacaranda is leafless from mid-March to mid-April, while the sweetgum and London plane (*Platanus acerifolia*) are leafless from the early December to early April, when most of the rainfall occurs. Because jacaranda retains foliage during most of the rainy season, they intercept more rainfall than the larger sweet gum. Camphor (*Cinnamomum camphora*) intercepted more rainfall than the taller red-flowering gum tree (*Eucalyptus ficifolia*) because of its

Table 3. Annual and peak event rainfall interception per tree (m^3)

Common name	Botanical name	Type	dbh (cm) 0–15.2	15.2–30.5	30.5–45.7	45.7–61.0	61.0–76.2	>76.2
			Annual					
London plane	*Platanus acerfolia*	BDL	1.24	6.46	12.82	19.62	25.99	31.40
Sweetgum	*Liquidambar styraciflua*	BDM	0.81	2.98	4.77	6.35	7.77	7.77
Jacaranda	*Jacaranda mimosifolia*	BDS	0.83	4.17	7.86	11.12	14.20	17.12
Red-flowering gum	*Eucalyptus ficifolia*	BEL	0.61	2.97	5.81	9.84	15.03	20.79
Camphor	*Cinnamonium camphora*	BEM	1.08	4.57	8.85	13.81	20.61	20.61
Carolina laurel cherry	*Prunus caroliniana*	BES	0.93	3.33	5.91	9.08	12.79	16.82
			Peak, 25-year storm (m^3)					
London plane	*Platanus acerfolia*	BDL	0.02	0.10	0.19	0.29	0.37	0.45
Sweetgum	*Liquidambar styraciflua*	BDM	0.01	0.04	0.07	0.09	0.11	0.11
Jacaranda	*Jacaranda mimosifolia*	BDS	0.02	0.18	0.37	0.53	0.67	0.81
Red-flowering gum	*Eucalyptus ficifolia*	BEL	0.04	0.12	0.23	0.42	0.72	1.19
Camphor	*Cinnamonium camphora*	BEM	0.07	0.14	0.28	0.43	0.83	0.83
Carolina laurel cherry	*Prunus caroliniana*	BES	0.04	0.10	0.19	0.34	0.58	0.90

larger crown projection area and greater leaf surface area. In Santa Monica, the amount of rainfall interception by individual trees depends on their foliation period and size, and tends to increase as foliation period, and leaf surface area increase. Similar rainfall interception patterns were observed for the 25-year storm (Table 3).

Rainfall interception for summer and winter events

Two storms with similar rainfall depth and temporal distribution and two tree species were selected to evaluate seasonal effects on rainfall interception. The trees were a deciduous sweetgum and evergreen camphor. The summer storm began at 14:00 on April 18, 1996, lasted for 44 hours, and resulted in 20.3 mm of precipitation. The winter storm began at noon on March 12, 1996, lasted 41 hours, and resulted in 21.7 mm of precipitation. The camphor had relatively high interception rates for both winter and summer events because the leaf surface area did not change seasonally (Table 4). The total amount of interception increased as dbh increased. Interception by the large sweetgum dropped from 70.5% during the summer rainfall event to only 5.5% during the winter event, when it was leafless. During the summer event, net precipitation (NP) (rainwater that reached the ground surface) was 29.5% of gross precipitation (GP), whereas interception and tree surface storage by the sweetgum

Table 4. Rainfall interception by dbh class for summer and winter events (m^3, %)

Tree species	Interception	dbh classes (cm)											
		0–15.2		15.2–30.5		30.5–45.7		45.72–61.0		61.0–76.2		>76.2	
Camphor	Summer event	0.1	68.4	0.2	26.9	0.4	24.4	0.6	28.7	1.0	35.0	1.5	41.6
	Winter event	0.1	54.3	0.2	19.3	0.3	19.4	0.5	19.8	0.7	22.8	1.0	24.2
Sweetgum	Summer event	0.1	42.8	0.3	52.5	0.7	70.5	0.9	70.5	1.1	70.5	1.3	70.5
	Winter event	0.0	5.4	0.0	5.4	0.1	5.5	0.1	5.5	0.1	5.5	0.1	5.5

was 70.5% of total precipitation. However, during the winter event, 94.5% of GP reached the ground surface as NP and interception accounted for only 5.5% of GP. Evaporation after summer storms reduced tree surface storage, thereby increasing interception during subsequent rainfall. Evaporation rates, seen as declining surface storage rates in figure 1, were lower during the winter storm than during the summer storm.

Discussion

These results indicate that interception is influenced by tree size and seasonal differences in foliation periods and rainfall patterns. Furthermore, interception is substantially greater on an annual basis than for a 25-year flood event (27% versus 7% at tree crown level). During flood events, relatively little interception occurs after the surface storage capacity is filled. The following discussion broadens our analysis by including data from different cities and describing implications for tree selection and management.

Tree pruning practices

Santa Monica and Modesto, California spend 56% and 46% of annual tree program budgets on pruning, respectively (McPherson and Simpson, 2002). Tree pruning can influence the magnitude of storm runoff reduction benefits by influencing crown volume and the amount of leaf and stem surface area. Most public trees are pruned on a 1- to 3-year cycle in Santa Monica, and a 3- to 4-year cycle in Modesto (McPherson and Simpson, 2002). In Santa Monica, a larger percentage of tree crown is removed with each prune than in Modesto to maintain sign clearance, storefront visibility, and ocean views. Relative to Modesto, more frequent and intensive crown raising, thinning, and reduction in Santa Monica may diminish rainfall interception. A simulation study was conducted to evaluate the extent to which pruning practices influence rainfall interception. Using tree growth curves for camphor and sweetgum trees in Santa Monica and Modesto, CA (Peper *et al.*, 2001a, 2001b), we simulated rainfall interception assuming both were located in Santa Monica (Figure 2).

Initially, sweetgum grows taller in Santa Monica than in Modesto, but after 15 years the Modesto sweetgum is taller, has more leaf area (LA), and greater crown projection

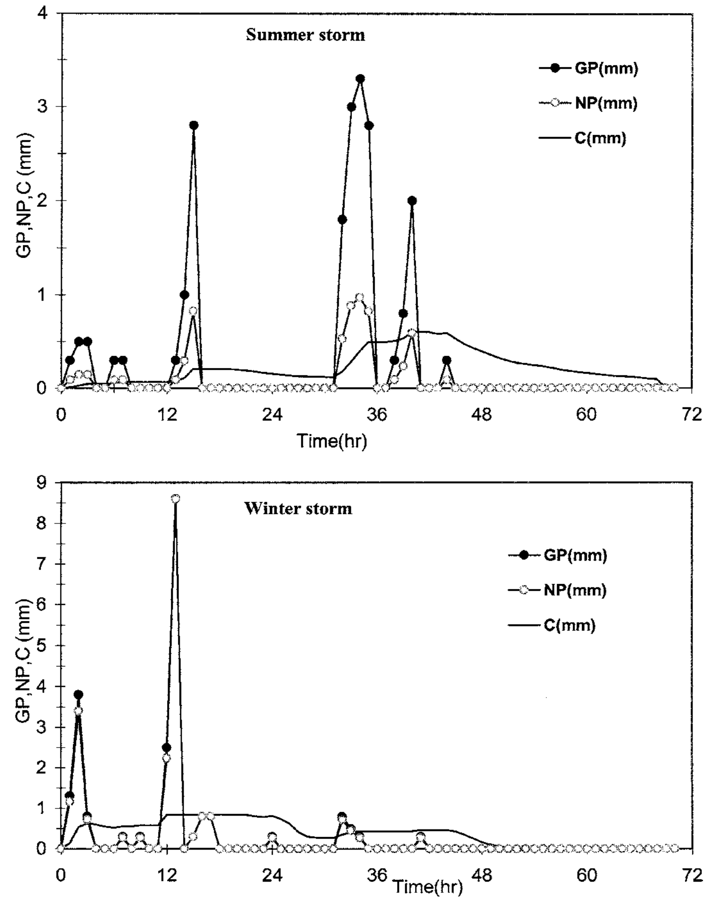

Figure 1. Rainfall interception dynamic processes of sweetgum tree during a summer and winter storm. GP is gross precipitation, NP is net precipitation, and C is tree surface storage.

area (CPA) (figure 2). After 40 years, the Modesto sweetgum's LA and CPA are twice that of the Santa Monica sweetgum. The crown volume of a 40-year-old sweetgum in Santa Monica is only 21.3% of the same aged tree in Modesto. We found similar dimensional differences for the camphor (crown height and LA) and other species growing in both cities. Because these differences persist across species, we attribute them primarily to more intensive pruning practices in Santa Monica, rather than different growing conditions and climate. As a result of these different crown dimensions, annual interception by the 40-year old Santa Monica sweetgum and camphor was only 46% and 65% of the Modesto sweetgum and camphor, respectively (figure 2). Hence, less frequent and intensive pruning in Santa Monica could increase rainfall interception rates while reducing expenditures. However, changing pruning practices may be resisted by residents accustomed to the current style.

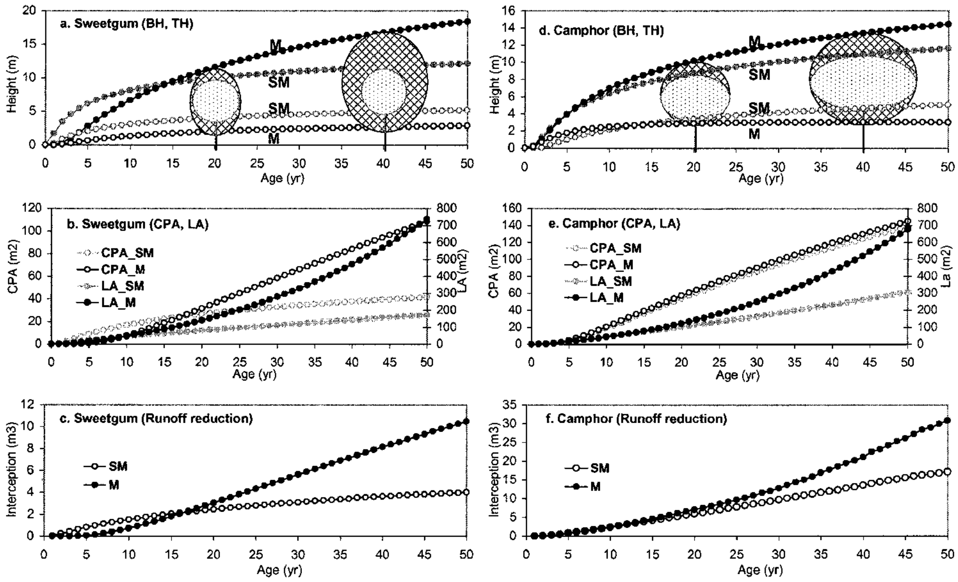

Figure 2. Architecture and runoff reduction of sweetgum and camphor trees. Here SM stands for Santa Monica and M for Modesto. BH is bole height, TH is tree height, CPA is crown projection area, and LA is leaf surface area.

Comparison with other cities

Annual rainfall interception per tree was greater in Santa Monica (6.6 m^3) than in Modesto (3.2 m^3, McPherson *et al.*, 1999) and Sacramento County, California (1.8 m^3, Xiao *et al.*, 1998). The reasons for these differences include the temporal distribution of precipitation, species composition and architecture, and meteorology. Both Modesto and Sacramento County are located in the Central Valley of California.

Figure 3 shows the temporal distribution of 'typical year' annual precipitation for these three areas. In 1992, rain fell during 59 days in Sacramento County, and there was no summer precipitation, typical for the region. One storm occurred in early February, and it brought 41% of annual precipitation. The remaining five storms that year brought another 45% of annual precipitation. In contrast, Santa Monica had a total of 106 rain days in 1996. The largest storm brought 24% of annual precipitation, and the next two largest storms brought only another 30% of annual precipitation. Other smaller storms brought 31% of annual precipitation during the summer and fall, when evaporation rates were high due to warmer air temperatures and increased irradiance. Greater rainfall during warmer periods partially explains why interception in Santa Monica was greater than in Sacramento and Modesto.

Table 5 shows the tree structure, leaf area distribution, and annual interception for these three areas. In Santa Monica, more than half (60%) of the public trees were broadleaf evergreens. They provided 51% of total leaf surface area and accounted for 57% of total annual interception. In Modesto, 88% of all public trees were deciduous and they provided

Table 5. Tree structure and annual rainfall interception in Santa Monica, Modesto, and Sacramento County

			Tree structure (% of total)							
	Annual interception		Tree number[a]				Leaf surface area			
Site	Per tree (m^3)	%	BD	BE	CE	PE	BD	BE	CE	PE
Santa Monica	6.6	27.3	6.4	59.9	11.1	22.6	6.6	50.5	32.2	10.8
Modesto	3.2	11.9	87.5	6.7	5.8	0.0	88.8	5.8	5.4	0.0
Sacramento	1.8	11.1	55.1	25.9	15.5	3.6	28.2	43.0	27.7	1.1

[a]BD = Broadleaf deciduous, BE = Broadleaf evergreen, CE = conifer, PE = Palm.

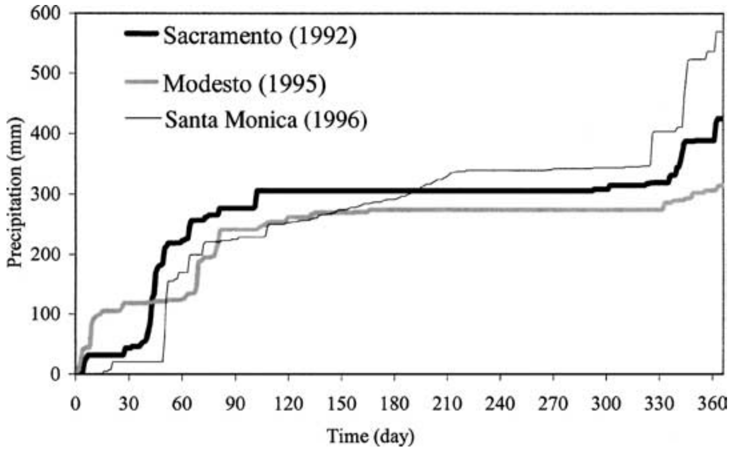

Figure 3. Temporal distribution of 'typical year' annual precipitation in Sacramento, Modesto, and Santa Monica.

89% of total leaf surface area. Rainfall interception in this deciduous tree-dominated urban forest averaged one-half that modeled for Santa Monica.

The percentage of evergreen trees was substantially greater in Sacramento County (45%) than Modesto (13%), but average tree size was smaller. In Sacramento, where all trees were sampled, the average crown diameter was 3.3 m. In Modesto, where only street and park trees were measured, the average crown diameter was 5.2 m. Rainfall interception at the tree canopy level was similar in Sacramento County (11.1%) and Modesto (11.9%), as were the precipitation patterns (more than 85% annual precipitation fell between December to March in both locations). To increase rainfall interception in these cities, managers can plant more broadleaf evergreens and conifers that will obtain large-stature and thus are more effective than deciduous trees where winter rainfall prevails.

Summary

Santa Monica's street and park trees intercepted 1.6% of annual precipitation (193,168 m^3, 6.6 m^3 /tree), providing avoided runoff benefits valued at $110,890 or $3.80 per tree. Large trees and evergreens were associated with the largest interception rates. Planting more evergreens and large-stature trees would increase these benefits in the long-term if the trees were well-adapted to local growing conditions. Also, future benefits could be increased if tree pruning practices were modified to retain more leaf surface area. However, this may conflict with other goals such as clear ocean views.

Acknowledgments

We thank Walter Warriner, the Santa Monica municipal forester for sharing his tree database with us. We thank Dr. Mike Miranda at Department of Public Works of Los Angeles for providing rainfall peak intensity-duration data. Paula Peper provided tree growth curves. This research was supported in part by funds provided by the Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture.

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