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Winter rainfall interception by two mature open-grown trees in Davis, California

Qingfu Xiao,*[1] E. Gregory McPherson,[2] Susan L. Ustin,[1] Mark E. Grismer[1] and James R. Simpson[2]

[1] *Hydrologic Sciences, Department of LAWR, University of California, Davis, CA 95616, USA*
[2] *USDA Forest Service, PSW, Western Center for Urban Forest Research and Education*

Abstract:

A rainfall interception measuring system was developed and tested for open-grown trees. The system includes direct measurements of gross precipitation, throughfall and stemflow, as well as continuous collection of micrometeorological data. The data were sampled every second and collected at 30-s time steps using pressure transducers monitoring water depth in collection containers coupled to Campbell CR10 dataloggers. The system was tested on a 9-year-old broadleaf deciduous tree (pear, *Pyrus calleryana* 'Bradford') and an 8-year-old broadleaf evergreen tree (cork oak, *Quercus suber*) representing trees having divergent canopy distributions of foliage and stems. Partitioning of gross precipitation into throughfall, stemflow and canopy interception is presented for these two mature open-grown trees during the 1996–1998 rainy seasons. Interception losses accounted for about 15% of gross precipitation for the pear tree and 27% for the oak tree. The fraction of gross precipitation reaching the ground included 8% by stemflow and 77% by throughfall for the pear tree, as compared with 15% and 58%, respectively, for the oak tree. The analysis of temporal patterns in interception indicates that it was greatest at the beginning of each rainfall event. Rainfall frequency is more significant than rainfall rate and duration in determining interception losses. Both stemflow and throughfall varied with rainfall intensity and wind speed. Increasing precipitation rates and wind speed increased stemflow but reduced throughfall. Analysis of rainfall interception processes at different time-scales indicates that canopy interception varied from 100% at the beginning of the rain event to about 3% at the maximum rain intensity for the oak tree. These values reflected the canopy surface water storage changes during the rain event. The winter domain precipitation at our study site in the Central Valley of California limited our opportunities to collect interception data during non-winter seasons. This precipitation pattern makes the results more specific to the Mediterranean climate region. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS precipitation; throughfall; stemflow; evaporation; interception; canopy interception dynamic processes; field instrumentation; measurement system; pressure gauge; urban forests; open grown trees

INTRODUCTION

Understanding the mechanisms and magnitude of canopy interception of precipitation is critical to water resources management for ecosystems and for characterizing moisture distribution, soil erosion, and pollutant concentration and distributions in hydrological studies (Clements, 1971; Monokaram, 1979; Sanders, 1986; American Forests, 1996). Storm-water management and flood control has been shown to benefit from canopy surface storage of intercepted rain water (Xiao *et al.*, 1998) and one study of urban

* Correspondence to: Q. F. Xiao, Department of Land, Air and Water Resources, c/o Department of Environmental Horticulture, University of California, Davis, CA 95616, USA.

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forests in the USA reported that 'the nation's forests are worth at least $400 billion in terms of storm-water management alone' (American Forests, 1996). Despite the importance of canopy interception in these processes, it has rarely been characterized systematically in order to understand how interception alters the timing and distribution of precipitation. Partitioning of gross precipitation or its redistribution as a result of vegetation interception is an important component in hydrological studies. Conceptually, canopy rainfall interception is the difference between gross precipitation (above canopy) and net precipitation (below canopy), or the fraction of the precipitation held by plant canopy surfaces. The intercepted water is stored on the canopy surface only temporarily, as ultimately it may fall to the ground around the tree bole as stemflow, or drip to the ground from leaves and branches, which contribute to throughfall; or evaporate directly from canopy surfaces to the atmosphere, contributing to interception losses. Rainfall interception processes are characterized by both rainfall dimension (size and type) and canopy architecture (Crockford and Richardson, 1990a). The canopy architecture, leaf area and leaf angle distribution, and even leaf surface characteristics (e.g., waxy or pubescent) all contribute to variability in interception and throughfall between different tree species.

Typically, free throughfall and stemflow are estimated as a fraction of gross precipitation (Rutter *et al.*, 1971; Jetten, 1996) using either an event or annual interception measurements without consideration of rainfall dimension (e.g., intensity and duration) or canopy architecture.

Based on interception studies in natural forests, a wide range of interception losses, throughfall and stemflow values have been reported. Zinke (1967) reported that interception loss is commonly 20% to 40% in conifers and between 10% and 20% in hardwoods. The amount of interception loss depends on the annual precipitation, meteorological factors such as wind speed, vapour pressure deficits, etc. and canopy structure (Rutter *et al.*, 1971; Crockford and Richardson, 1990a). Stemflow and throughfall were measured as 13% and 58% of gross precipitation in a mature Sitka spruce forest (3450 trees ha^{-1}) (Anderson and Pyatt, 1986). Interception loss was 28% in a 50-year-old Sitka spruce forest in Scotland, but stemflow was only 3% of gross precipitation (Johnson, 1990). Based on a study of four *Eucalyptus melanophloia* trees (110 trees ha^{-1}) in Australia, Prebble and Stirk (1980) found that interception losses accounted for 11% of annual precipitation with only 0·6% as stemflow. In southern Scotland, Ford and Deans (1978) found that 30% annual precipitation was lost via canopy interception, but stemflow was as high as 27% of annual precipitation in a 14-year-old *Picea sitchensis* plantation (3594 trees ha^{-1}). Similarly, Pook *et al.* (1991) observed interception losses of 26·5% and 8·3% in gross pine and eucalypt plantations (1493 trees ha^{-1}), respectively, in the Upper Shoalhaven Catchment, Australia. Also in Australia, Crockford and Richardson (1990a) showed that the interception losses accounted for 11·4% of annual precipitation in eucalypt forest (1525 trees ha^{-1}) and 18·3% for pine forest (1708 trees ha^{-1}). Interception loss accounted for 12·6% to 21·0% of annual precipitation in a maritime pine stand forest (800 trees ha^{-1}) in south-west Europe (Loustau *et al.*, 1992a). These studies were conducted in natural forests where canopy architecture and tree spacing is different than in open-grown trees commonly planted in urban areas. Results reported from natural forests may not be transportable to open-grown sites, because of differences in tree architecture and micrometeorological factors. Even in sparse natural forests, interception processes differ from those in dense natural forests (Gash *et al.*, 1995). Stogsdill *et al.* (1989) found that throughfall increased 3% with every 4 m ha^{-1} reduction in basal area. More field observations and experimental measurements of rainfall interception processes under differing conditions of rainfall dimensions and canopy architectures are needed to better understand these processes.

Quantification of canopy rainfall interception processes is dependent largely on the measurement and monitoring methods used. It has been estimated that commonly used sampling and measurement techniques cause large errors in estimated interception (Sevruk, 1986; Crockford and Richardson, 1990b). Measurement accuracy and temporal resolution are determined by the measuring system, which includes sampling design and data collection. Improving sampling design can reduce the sampling error (Chen *et al.*, 1995) but not the error introduced by measurement equipment. Point measurements generally are accomplished using funnels (Ford and Deans, 1978; Navar and Bryan, 1990; Cape *et al.*, 1991; Teklehaimanot *et al.*, 1991; Bouten *et al.*, 1992; Giacomin and Trucchi, 1992; Hansen, 1995; Li *et al.*, 1997) or rain gauges (Lloyd *et al.*, 1988; Loustau *et al.*, 1992b) placed directly beneath the canopy. Although easy to perform, such measurements often have large data sampling errors (Kimmins, 1973). Based on throughfall measurements of four 30 m by 30 m plots in a 120-year-old forest, Kimmins (1973) found that several hundred gauges were required in order to reduce error in the estimated mean throughfall from 20% to 5% (also see Kostelnik *et al.*, 1989).

Reynolds and Neal (1991) reported that there was no statistically significant difference between the total annual amounts of throughfall collected by funnels and troughs. However, when a large number of point gauges are required, area measurements are sometimes used. Area measurements may use plastic sheeting (Calder and Rosier, 1976; Neal *et al.*, 1993) or troughs (Horton, 1919; Hamilton and Rowe, 1949; Rutter *et al.*, 1971; Crockford and Richardson, 1990b; Kelliher *et al.*, 1992; Liu, 1997) combined with tipping buckets or weighing gauges to obtain integrated throughfall measurements over a large area. These methods yield spatially correct averages but adhesion of rain water to the sheeting or other losses (such as splashing), combined with possible blockage of the collection gutter during large storms (Teklehaimanot *et al.*, 1991) may cause large and unpredictable measurement errors. Even area measurement methods may cover only a limited measuring area as compared with the size of tree crown projection areas, so that the measurement error often remains considerable, even though it is less than that from the point measurement method. Some of these methods have low temporal resolution as a result of infrequent sampling (measuring events, weekly, or monthly periods).

Aston (1979) weighed a tree during simulated rainfall in a laboratory in order to study the dynamic aspects of canopy interception processes. The dimension of the rainfall simulator required to weigh large trees restricted this study to quite small trees, making the extrapolation to mature tree canopies questionable. More recently, the load-cell method proposed by Lundberg *et al.* (1997) has advantages of both point (easy to perform) and area measurement methods (spatially correct averages). The load-cell method provides relatively accurate estimates of interception combined with high temporal resolution in natural forests, except during periods of high wind. Sampling errors are not always reduced in the load-cell method because the troughs may cover only a small portion of the total forest area.

The structure and maintenance methods for tree plantations are significantly different than natural forests. This results in greater heterogeneity of tree species and their spatial dimensions in urban settings in contrast to natural forests. Trees generally are isolated, with large distances between them, thus there is less interaction of interception water between trees (such as leaf drip from adjacent trees) than observed in natural forests. In an interception study on a sparse natural forest, Gash *et al.* (1995) found that interception processes are different to those in dense forests. Wind associated rainfall can change the throughfall distribution. With high wind, rainfall strikes the canopy at zenith angles greater than that associated with no wind, when it is delivered vertically to the crown projection area. When point or partial area sampling methods are used for open-grown trees, large measurement errors result from the mixing of rainfall and throughfall. Variations in leaf surfaces and stem surface areas, as well as gradients of microclimate in the landscape or within an individual tree, suggest that partial area measurements will induce a substantial error when applied to open-grown trees.

Precipitation coincident with high wind speeds also changes the proportions of stemflow and throughfall associated with canopy interception. Calder and Wright (1986) described the difficulties in measuring this partitioning of interception accurately. Herwitz and Slye (1995) found that the variation in total net rainfall among neighbouring trees was affected by the differential interception of inclined rainfall.

The disadvantages of point methods (large measurement error or many gauges needed), area methods (measurements based on partial sampling of the canopy crown projection area, potential for adhesion loss and splashing), and load-cell methods (wind affects) limit their application for urban forest rainfall interception studies. Neither the point nor area methods mentioned above work well for isolated trees. The ideal system for measuring urban tree rainfall interception has at least the following four features:

1. measurements must be made at the individual tree level instead of partial measurements of the tree crown projection area to avoid sampling error;

2. measurements must have high accuracy and high temporal resolution;
3. the measurement system must work under all weather conditions, including high wind speeds;
4. the measurement system should be built at low cost and be transported easily.

In this paper, we present a study of the rainfall interception processes for open-grown trees common to urban settings. Initially, we developed a rainfall interception measuring system that is suitable for use with individual trees. Then, we partitioned gross precipitation into throughfall, stemflow, crown storage and interception, and analysed the effects of temporal scales on dynamic rainfall interception processes. Finally, we analysed the effects of both climate (i.e. rainfall rate and duration, wind speed and direction) and tree architecture (i.e. tree height, crown shape, leaf and stem surface areas) on crown rainfall interception.

DEFINITION OF TERMS

The terminology used in canopy rainfall interception studies has not yet become consistent or standardized. Many investigators have termed the 'interception' as the difference between the rainfall measurements over open ground and the measurements under the canopy crown; others have termed this difference as 'interception loss'. When we evaluate canopy rainfall interception at the event scale, the term 'interception' and 'interception loss' are close in meaning. When we refer to the dynamic aspects of interception, however, the terms 'interception' and 'interception loss' have different physical meanings. Interception here indicates the temporary rain-water storage on the canopy surface. Interception loss indicates the evaporation of temporarily stored rain-water on the canopy surface. In order to clarify the discussion, the following definitions are used.

Gross precipitation (P_g) is the precipitation measured above the vegetation canopy or in the open area where the fetch is sufficient to avoid the forest edge or topographic effects.

Net precipitation (P_n) is the quantity of rain water that actually reaches the ground. It is the sum of throughfall and stemflow.

Free throughfall (*Th*) is the rain drops (a fraction of precipitation) that reaches the ground surface through the gaps in the canopy leaves and branches without hitting the canopy surfaces (Rutter *et al.*, 1971; Dingman, 1994).

Canopy drip (*D*) is the water drip from canopy surfaces that occurs when the canopy surface rain-water storage exceeds its storage capacity. It also can occur when the equilibrium status of the tree surface water storage decreases as a result of impact ejection from rain drip or mechanically, from wind blowing the tree.

Throughfall (*TH*) is the portion of the precipitation that reaches the ground directly through gaps in the vegetation canopy and drips from leaves, twigs and stems. It is the sum of free throughfall (*Th*) and canopy drip (*D*).

Stemflow (*ST*) is the portion of precipitation intercepted by the canopy and reaches the ground by flowing down the stems or tree bole.

Canopy storage (*C*) is the precipitation that falls on the vegetation surfaces (canopy) or human-made cover and is temporally stored on these surfaces. Intercepted water either can be evaporated directly to the atmosphere, absorbed by the canopy surfaces, or ultimately transmitted to the ground surface.

Interception (*I*), same as canopy storage (*C*).

Interception loss (*IL*) is the portion of the precipitation that is retained by canopy surface storage and later is either evaporated or absorbed by the plant.

Storm and rainfall event: an individual storm is defined as a rainfall period separated by dry intervals of at least 24 h and an individual rainfall event is defined as a rainfall period separated by dry intervals of at least 4 h (Hamilton and Rowe, 1949).

For consistency, the canopy rainfall interception concept we use is contrasted with other literature definitions. We use crown rainfall interception instead of canopy interception because of our focus on isolated mature trees. The crown surface includes both crown (e.g. leaves, branches, and stems) and tree bole surfaces.

THEORY

Rainfall interception

Rainfall interception includes the processes that result from the temporary storage of precipitation by the tree canopy as described above. Interception can be described as the difference between gross precipitation (P_g) and net precipitation (P_n). At a more detailed level, interception can be partitioned into canopy surface water storage (C) and evaporation (E), and net precipitation can be partitioned into throughfall (TH) and stemflow (ST). Throughfall can be further separated into free throughfall (Th) and canopy drip (D).

$$C + E = P_g - (Th + D + ST) \tag{1}$$

Equation (1) can be solved for interception (I, or $C + E$) with knowledge of the gross precipitation term (P_g) and net precipitation term (Th, D, and ST). Canopy storage can be determined after estimating the evaporation term (E).

Net precipitation method

The net precipitation method is widely used in rainfall interception studies because all components on the right side of Equation (1) can be measured directly. Free throughfall and canopy drip can be separated based on the analysis of measured rainfall and throughfall data (Rutter *et al.*, 1971). Based on these measurements we can determine interception. In some cases not only do we want to know the interception or interception loss for each event but also dynamic changes in canopy water storage during the event. From field observations, the duration of canopy drip continues after the rainfall ceases. This indicates that canopy surface water storage can exceed its capacity temporarily, or overstore, and the wind may affect this capacity. For example, dripping after the rainfall ceases also can be a result of wind. Canopy water storage is easily measured indirectly. The estimation accuracy is determined by the measurement accuracy of the terms on the right-hand side Equation (1). For example, using the Penman method (Jetten, 1996) to estimate evaporation, we can solve Equation (1) for canopy storage (C). The accuracy of evaporation (E) is determined largely by the accuracy of the direct measurements for parameters in the Penman method (e.g., net radiation, air temperature, vapour pressure and wind speed, Penman, 1948).

FIELD EXPERIMENTS

Rainfall interception measurement system

The TH, ST, P_g, and micrometeorological data required for estimating E are measured directly. The measurement system is composed of two parts. The first part measures P_g, TH and ST. The second part is a micrometeorological station measuring air temperature, relative humidity, wind speed, wind direction, and net radiation. These two parts are linked to a CR10 datalogger (Campbell Scientific Inc.). Figure 1 shows a schematic description of the rainfall interception measuring system. A spiral guide strip around the tree bole collects stemflow. A catchment built under the tree collects all water falling inside the catchment (TH and P_g). The TH value was determined by the water collected under the canopy crown projection area, and the remaining rainfall captured by the catchment was excluded. Gross precipitation (P_g) was collected with a glass funnel connected to a container at the upwind corner of the catchment. Evaporation (E) was estimated using the Penman equation based on meteorological data obtained adjacent to the experimental site.

Throughfall measurement. A catchment was constructed under each tree to collect incident precipitation on to the tree. The catchment consisted of two panels with sloping sides (angle dependent on the tree size and

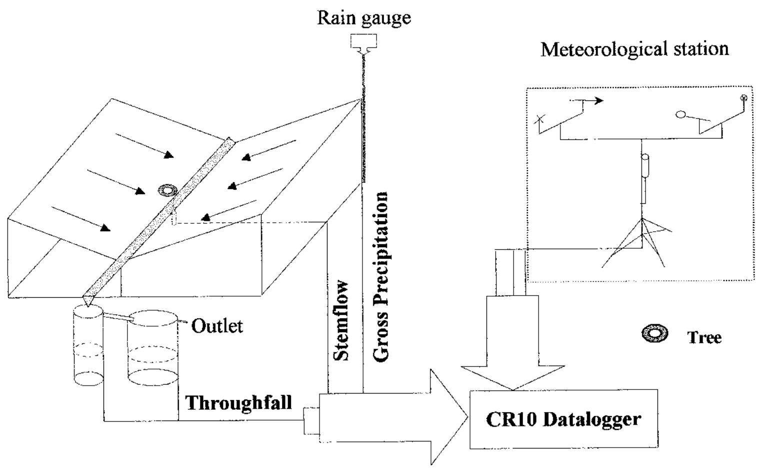

Figure 1. Schematic description of rainfall interception measuring system

shape) linked together by a plastic rain gutter. The tree is located in the geometric centre of the catchment. The catchment base frame was constructed from sheets of 122 × 244 cm (4 × 8 ft) plywood, overlaid on to a 5 × 10 cm (2 × 4 in) frame, and lined with 0·15 mm (4 mil) plastic sheeting on the plywood. The water division line of the catchment terminated in a raised 5 × 2·5 × 5·7 cm (1 × 2 × 2·2 in) wood border having a triangular cross-section attached to all edges of the catchment beneath the plastic sheeting, except the edge linked to the rain gutter. The vertex of the pieces forced water to flow either inside or outside the catchment. The rain gutter guides the water into the throughfall storage container. To make the system work well for both small and large rainfall events, small diameter 20·3 cm and large diameter 30·5 cm water containers were used to store the water collected from the catchment. The water depth increases in the small diameter container so it can quickly respond to small throughfall increments in small rainfall events. The small and large containers were linked together by a 2·54 cm diameter PVC pipe, located near the upper rim of the large container, 5·1 cm below the upper edge, with a 12·5% slope. Water fills the small container first and then automatically flows to the larger container when the small container is full. There is also a second outlet in the larger container 5·1 cm below the rim to protect the container from overflow. A pressure gauge (PG), constructed from a pressure transducer, was attached to the bottom of each container to monitor changes in the water level inside the container, thus permitting frequent water-level measurements to be recorded accurately. The catchment construction height was near the bottom of the crown, so that it does not influence turbulence and thereby the vertical mixing of humidity. The water containers were covered with plastic sheeting to prevent rainfall from directly entering the container. Based on a mass balance, throughfall is determined by the difference between the water collected in the throughfall container, catchment surface detention storage and the P_g falling outside of the crown drip line.

Stemflow measurement. Stemflow was collected directly from the tree bole using a channel fabricated from a 2·54 cm diameter soft Tygon tubing that was split and spiralled around the tree bole. Gaps between tubing and tree bole were sealed with clear 100% silicone sealant. A water container made from 7·62 cm diameter solid clear tubing was used for stemflow storage. The water level change inside the container was monitored using a pressure gauge (PG).

Gross precipitation measurement. Gross precipitation was collected with a 15·2 cm diameter glass funnel linked to a gross precipitation container set at the upwind corner of the catchment. The container was made of 2·54 cm diameter solid clear tubing. The water depth inside this container was measured using a PG. The height of the water collection funnel is 3·0 m above ground surface.

Micrometeorological station. A standard micrometeorological station was established over turf grass for reference. Data from the micrometeorological station were used for estimating evaporation. A HMP35C Temperature and Relative Humidity Probe (Campbell Scientific, Inc.) was used to measure air temperature and relative humidity, wind speed and direction were measured with R.M. Young Wind Sentry Set (03001-5, Campbell Scientific, Inc.), solar radiation and net radiation were measured with a LI200S Pyranometer (Campbell Scientific, Inc.) and a Q-6 Net Radiometer (Campbell Scientific, Inc.) respectively, and a TE525 Tipping Bucket Rain Gage (Campbell Scientific, Inc.) was used to measure gross precipitation on the study site in addition to the PG rain gauge. The TE525 is a smaller adaptation of the standard Weather Bureau tipping bucket rain gauge. It measures rainfall at rates up to 51 mm h^{-1} (2·0 in h) with an accuracy of $\pm 1\%$.

Data collection and calibration. Gross precipitation, throughfall, stemflow and all data measured in the micrometeorological station were sampled at 1-s intervals and collected at 30-s time steps with a CR10 datalogger (Campbell Scientific, Inc.). Both the data sampling frequency and data output time step were controlled with the datalogger program. All instruments used for micrometeorological data collection were calibrated against CIMIS (California Irrigation Measurement Information System) station data at the UC Davis site, except for the LI200S, which was calibrated by the manufacturer. All PGs were tested in the laboratory before use in the field and a final calibration was conducted in the field (Xiao, 1998). Water storage containers used in this study were circular high-pressure PVC cylinders. The volume of water collected changed linearly with the water depth inside the container. A regression between the volume of water in each container and the pressure voltage reading was linear, with a R^2 of 1·0 indicating that the system measured accurately. A detailed description of the pressure transducers and their calibration is presented in Xiao (1998).

Accuracy estimation. Measurement accuracy depended on the pressure transducers used, the ratio of water collection area to the horizontal cross-section area of the water storage container and the time for water to travel from the water collection surface to the container. A large ratio causes a large change in the container's water depth. The pressure transducers (Honeywell model No. 136PC01G2) used in this study were designed for indoor use. The pressure transducers worked well spanning a large temperature range ($-40\,^{\circ}$C to $+85\,^{\circ}$C), but needed to be kept dry. Submerging the transducer will cause it to malfunction. We used 2·54 cm diameter solid tubing with a rubber stopper at the bottom to avoid submerging the transducer in case of overflow. A 3·8 cm diameter cap allowed the transducer to reference the atmosphere but prevented water from entering. A slave tube filled with desiccants hung inside the 2·5 cm tubing adjacent to the transducer to reduce moisture and maintain relatively constant humidity. This minimized variation in reference transducer output. The measurement system successfully monitored dynamic processes for each individual event, during which changes in air temperature and impacts on the measurements are presumed to be small because of the low temperature gradients that were recorded. Direct power for the system was provided by 12 V DC batteries (YUASA-EXIDE, Inc.). The batteries were in a plastic-covered wooden box to reduce the battery's temperature change with time, because the chemical reaction of the battery is temperature sensitive. Calibrations for power supply voltage and temperature changes were also obtained in the field. A constant water depth was maintained in the container in the field and we ran the system for a 24-h period to obtain data for this calibration. For example, air temperature varied over a large range (12·9 °C), but the PG reading only changed 0·0735 mv or 0·000238 mv $^{\circ}C^{-1}\,h^{-1}$. This indicates that the PGs were only slightly influenced by the temperature gradient. The installation of the pressure transducer gauges was described in Xiao (1998).

The pressure transducer used in this study has an error of less than $\pm 0{\cdot}5\%$ over its span. The gross precipitation measurement system had the smallest ratio of water collection area to water container area (36:1) with a measurement error of 0·04 mm. The error associated with detention storage and water travel time to the collection system was reduced by the steep inclination angle of the catchment and smooth surface of the plastic sheeting. Detention storage and water travel time was measured directly in the field. A day with heavy cloud cover and high relative humidity was selected for measuring detention storage in order to minimize evaporation during data collection. The catchment surface detention averaged 0·3 mm for the first experimental site and 0·045 mm for the second site. Water travel time was about 1·5 and 0·5 min for these sites during small events, respectively. This time delay did not affect the analysis of data at the event scale. The relatively steeper inclination angle and smaller size of the second catchment account for its lower detention storage and shorter travel time compared with the first site. The measurement of catchment detention storage and water travel time was described by Xiao (1998).

Canopy architecture measurement. Tree dimensions, which include height, DBH (diameter at breast height), crown diameter, crown shape and crown height, and canopy architecture data, which include leaf surface area stem surface area and crown gap fraction, were measured directly after the experiment ended. The gap fraction was estimated as the percentage of crown silhouette area without leaves or branches using an image analysis technique. The gap fraction is thought to be related to free throughfall.

Stem surface area was measured for each branch by first dividing the branch into several uniform segments and then measuring the length and the diameters at both ends of each segment. About 10% of the leaves were removed from the tree using a random branch sampling technique to determine leaf area. The remaining leaves were removed from the tree and oven dried (70 °C, 72 h). Sample leaves were measured in a LI-3100 area meter (LI-COR, Inc.). The resolution of the measurement is about 1·0 mm^2. The dry weight ratio method was used to determine total foliar biomass and leaf area. Seasonal changes in leaf area were measured by periodic collection of leaf fall. We did not measure the change in leaf area during the growing season because there were almost no rainfall events during this season at our study site. The leaf area change during the growing season, however, can be measured using photographic methods (Peper and McPherson, 1998). Above-ground woody biomass of the tree was obtained directly by measuring fresh and dry weight at the end of the experiment. Techniques used for measuring tree architecture, leaf surface area, stem surface area and biomass are described by Xiao (1998).

Study sites and materials

The rainfall interception experiments were conducted at the Department of Environmental Horticulture field site, in the south-east corner of the University of California, Davis campus (121°46′32″ W, 38°32′09″ N). This site is located in the Central Valley of California. Moisture comes from the southern side of the study site owing to the influence of mountain ranges. The Sierra Nevada Mountain Range blocks moisture from the east. The California Coast Range is located to the west, and Sutter Buttes are volcanic remnants located in the Central Valley to the north. These mountains obstruct wind patterns for moisture transport to the study site from these directions. The relatively flat topography on the south side of the study site extends south-west to the Pacific Ocean, and the orientation of this flat terrain controls the direction of most of the precipitation at the study site. About 70% of the experimental field was covered by grass and 30% by bare soil. On average, 90% of the average annual precipitation of 446 mm (CV = 36 mm), which ranged from 143 mm in 1976 to 969 mm in 1983 (based on 1927–1997 hourly data at the Davis NOAA station number: 2294, located at 121°46′ W, 38°32′ N), occurs between November and April at the study site. No snowfall occurred in the study area. The rainfall intensity ranges from 1 to 113 mm h. The rainfall is heaviest during winter storms, which delivers most of the annual precipitation. For example, three storms (total 175 mm) occurring in January 1997 (3, 20 and 24 January) accounted for 42% of the 414 mm of annual precipitation in 1997. During our experiments, the rainfall intensity ranged from 1 to 28 mm h^{-1}, as recorded at our field experiment site. Interception data were collected from a 9-year-old broadleaf deciduous pear tree (*Pyrus calleryana* 'Bradford' or Callery pear) and an 8-year-old broadleaf evergreen oak tree (*Quercus suber* or cork oak) (Figure 2). The pear tree and the oak tree were open-grown and separated by about 63 m. The canopy dimensions of these two trees are listed in Table I. Unlike the evergreen tree, which showed little change in leaf surface area (leaf area index, LAI = 3·4) over the year, the broadleaf deciduous pear tree had high leaf area in summer (LAI = 7·0), but was almost leafless during the winter season. The catchment size of the pear tree site was 62·4 m^2 with a 15° inclination angle. The catchment size was 23·0 m^2 with a 25° inclination

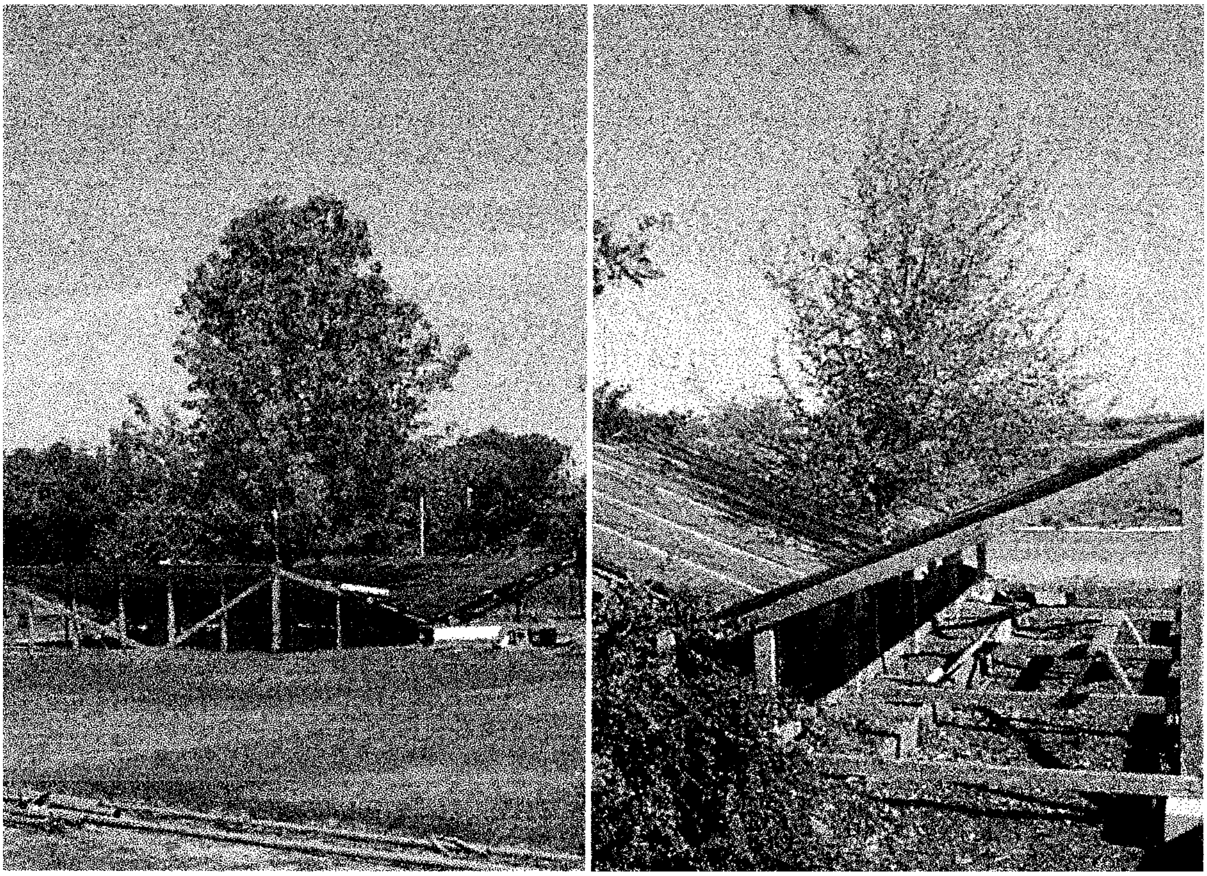

Figure 2. Field installation for pear tree (left) and for oak tree (right)

Table I. Dimensions of the experimental trees

	Oak (cork oak)	Pear (callery pear)
Height (m)	5·6	8·5
DBH[a] (cm)	12·5	22
Crown diameter (m)	3·2	4·8
Crown height (m)	4·77	6·8
Crown shape	Paraboloid	Paraboloid

[a]Diameter at Breast Height. Both trees had branches below breast height (1·3 m or 4·5 ft), so the bole diameter was measured immediately below the first branch where there was no lateral expansion resulting from branch growth.

angle, respectively, for the oak tree. The micrometeorological station was 20 m from the oak tree site and 70 m away from the pear tree site.

For the analysis conducted here, we used data collected over the winter of 1996–1997 for the pear tree and over the winter of 1997–1998 for the oak tree. The annual precipitation of 1996–1997 water year was 441 mm, distributed in 38 storms. Three large storms (rainfall > 38 mm) account for 41% of the total annual precipitation whereas 20 small storms (rainfall < 3·17 mm) accounted for only 6% of the annual precipitation. In contrast, 1997–98 was a wet water year in which more than 700 mm of precipitation fell before June 1998 in 46 storm events. Half this rainfall came in five large storms whereas 11 small events accounted for only 3% of the total precipitation. Table II(a and b) summarize the precipitation distribution at different time-scales for both the long-term average and for the period during which field experiments were conducted.

Partitioning gross precipitation

Rearranging Equation (1), the total gross precipitation (P_g) in a vegetated area can be expressed by

$$P_g = C + E + D + ST + Th \tag{2}$$

Free throughfall (Th) is proportional to the gap coefficient (f_g), which can be taken as the gaps between crown leaves or branches normal to the direction of incident rainfall

$$Th = f_g P_g \tag{3}$$

Table IIa. Precipitation distribution at monthly scale

Statistical data			Experimental data					
Month	Average (mm)	Coefficient of variation	1996	Departure from normal	1997	Departure from normal	1998	Departure from normal
1	94·9	0·7	—	—	185·9	91·0	124·0	29·1
2	79·3	0·8	—	—	7·1	−72·2	298·0	218·7
3	63·5	0·8	—	—	10·9	−52·6	47·0	−16·5
4	30·0	1·1	—	—	3·0	−26·9	32·0	2·0
5	11·9	1·2	—	—	8·9	−3·0	59·0	47·1
6	4·6	1·6	—	—	5·1	0·5	2·0	−2·6
7	0·5	4·3	—	—	5·1	4·6	—	—
8	0·9	2·9	—	—	4·1	3·2	—	—
9	5·2	2·2	—	—	8·9	3·7	—	—
10	22·4	1·3	—	—	10·9	−11·5	—	—
11	52·2	0·9	—	—	108·0	55·8	—	—
12	80·7	0·7	170·9	90·2	55·9	−24·8	—	—

Table IIb. Precipitation distribution at storm and event scale

Precipitation (mm)	Pear tree site		Oak tree site	
	Number of storms	Number of events	Number of storms	Number of events
< 5	8	30	11	54
5–10	3	3	6	13
10–15	1	2	6	10
15–20	0	0	2	2
20–25	0	1	5	4
25–30	0	1	1	2
30–35	1	3	2	4
35–40	2	1	1	0
40–45	0	0	0	0
45–50	1	0	0	1
50–55	0	0	1	0
> 55	2	1	3	2
Total precipitation (mm)	332		791	
Total storms	18		38	
Total events		42		92

Evaporation (E) from a wet crown surface is estimated indirectly from micrometeorological data. We assume that when the crown surface was saturated, the evaporation of crown surface water occurred at the potential rate, otherwise it was proportional to the ratio of actual storage and saturation storage or the maximum storage capacity of the crown (Rutter *et al.*, 1971). Potential evaporation from wet surfaces was estimated using the Penman equation (Penman, 1948), using data measured at a nearby micrometeorological station. The dry wind function for solving Penman's equation used here followed Pruitt and Doorenbos (1977a,b).

The (C) or crown storage pool is filled by rainfall and emptied through E, D and ST. Crown storage C and interception loss E contribute to interception I, which is the intercepted water temporarily stored on the crown surface. Free throughfall Th and drip D yields throughfall TH. The sum of TH and stemflow ST is the net precipitation P_n

$$\begin{aligned} I &= C + E \\ TH &= Th + D \\ P_n &= TH + ST \\ P &= I + TH + ST \end{aligned} \tag{4}$$

Measurements of P, TH and ST were undertaken directly during the field experiments, such that I could be calculated. The error or accuracy of the interception calculation from this water balance is determined by the measurement accuracy for P, TH and ST, with P having the greatest potential error in this measuring system, which we estimated (described in the accuracy estimation section) as 0·04 mm maximum error. The most significant errors are in the collection system, e.g., the result of wind affecting surface detention storage, or other problems associated with the collection apparatus.

RESULTS AND DISCUSSION

High temporal resolution and accurate measurements of canopy rainfall interception at the individual tree level can be obtained using this interception measurement system. The rainfall interception measuring system is reliable and easy to build. Splashing did not cause a problem because the boundary was well defined. The large size and inclined rain gutter provide sufficient water transport capacity such that blocked gutters were not a problem during heavy rainfall. Winds did not affect the measurements. Some data collected during very high wind periods, however, would not be used for throughfall analysis because the catchment was not large enough to catch the canopy drip when wind speeds were greater than 15·0 km h^{-1}, as recorded at the micrometeorological station. This problem may solve by enlarging the catchment dimensions. The measurement is dependent on both rainfall amount and the storage capacity of the container; frequent emptying of the container is necessary to avoid overflow and loss of data during large rainfall events. The system was not designed to measure snow interception, however, a detailed discussion and review for existing and new measurement methods for snow interception was presented by Lundberg (1993).

The results presented here include 63 events measured between December 1996 and February 1998. These data were from 56 storms (134 events) that were large enough to result in measurable throughfall or stemflow and for which complete data were recorded. Monthly distribution of these precipitation data are presented in Table IIa. Table IIb shows the precipitation distribution in storm and event scales. Rainfall events associated with storms having wind speeds greater than 15 km h^{-1} were eliminated because there was a possibility that crown drip could be blown beyond the tree catchment. The threshold of wind speed was determined based on the tree height and catchment size, whereas canopy drip was assumed to start from zero velocity. Three rainfall events were eliminated from further analysis for the pear tree when wind speeds of 18·8 km h^{-1} to 29·5 km h^{-1} were recorded during a storm on 21 January 1997, and another event that occurred on 2 March 1997 when the wind speed was 18·2 km h^{-1}. Gross precipitation in these three events was 6·5 mm, accounting for 2% of the total rainfall data. Figure 3 shows a hyetograph for cumulative

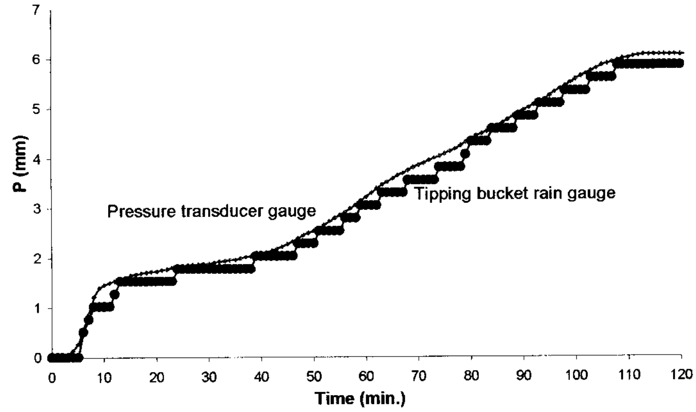

Figure 3. A hyetograph showing cumulative precipitation measured with PG and tipping bucket rain gauges

rainfall measured with a PG and a tipping bucket rain gauge. The two data sets matched well in magnitude except that the PG data set has greater temporal resolution because the tipping bucket needed 0·25 mm increments of rainfall to record.

The high temporal resolution of the data allowed data analysis at different time-scales. Here we focus on the analysis at the event-scale (from hours to 1 day) and the dynamic or process-scale (minutes). The gross precipitation was partitioned into throughfall, stemflow and interception losses.

Average interception losses. At the event scale, based on the regression results of these events, we conclude, on average, that throughfall and stemflow account for 77% and 8% of gross precipitation respectively, for the pear tree. For the oak tree, throughfall and stemflow account for 58% and 15% of gross precipitation, respectively. Statistical averages of these components are discussed in more detail later.

Most rainfall events at our study site were relatively small (<2 mm). These small events resulted in relatively high interception losses because most of the water from the event is used to wet the crown surface. In the following discussion, a large rainfall event on 12 January 1998 is used to illustrate the dynamics of crown rainfall interception. This event lasted about 10 h with a 104 min break in the middle, maximum 30-s intensity about 12·5 mm h^{-1}, and the total precipitation was 13·0 mm. Figure 4 shows the dynamic nature of rainfall interception on the oak tree at the subevent-scale for 1 min, 5 min, 10 min, 30 min, and 60 min time intervals. We show the accumulative values for the first 5 h of the event (Figure 4a–e) and the rate changes for this period (Figure 4f–j). Thirty minutes after rainfall was initiated, there was little variation in rainfall intensity, but throughfall, stemflow and interception varied markedly with time. Stemflow started 20 min after rainfall started. After rainfall stopped, both stemflow and throughfall continued for an additional 60 min and 47 min, respectively. Evaporation was limited because of the high relative humidity. Relative interception loss was high during the early stages of the event but decreases when rainfall increases. This indicates that crown surface water storage accounts for the main portion of interception loss. The same patterns were found for the pear tree. Interception processes varied less between trees with increasing temporal averaging. The fine features are not detectable in Figure 4j at the 1-h time resolution, an interval that is commonly used in general hydrological, ecological and meteorological modelling.

Interception accounts for the difference between gross rainfall and the sum of throughfall and stemflow. Water losses from crown surfaces as a result of evaporation are included in interception losses, but none occurred during this rainfall event. After stemflow and crown drip, the wet crown surface was dried by evaporation. Although evaporation was negligible during the rain event, it gradually increased after rainfall ceased. Thus, frequent precipitation events increase the relative proportion of interception losses.

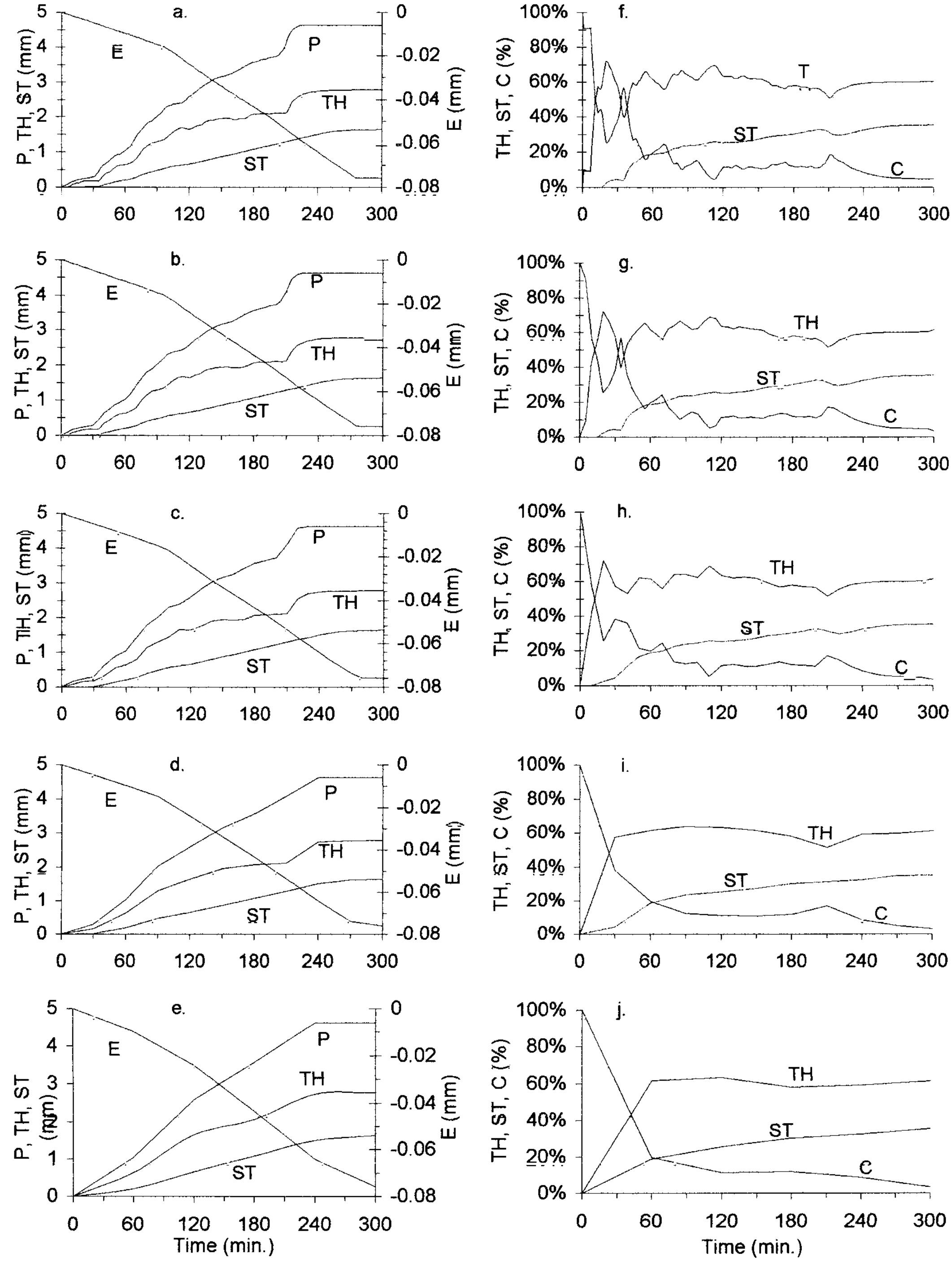

Figure 4. Dynamic rainfall interception processes on the oak tree at different time-scales: *P*, *TH*, *ST*, *E* and *C* are precipitation, throughfall, stemflow, evaporation and tree surface storage. The horizontal axis represents the time in minutes. The vertical axis for panels a, b, c, d and e are cumulative water depth in millimetres. The left vertical axis represents the scale for cumulative *E* in millimetres. In panels f, g, h, i and j, the vertical axis shows the *TH*, *ST* and *C* in percentage of precipitation. Panel a, b, c, d and e show the accumulation of rainfall, throughfall, stemflow and evaporation for time-scale at 1 min, 5 min, 10 min, 30 min and 60 min. Panel f, g, h, i and j show throughfall, stemflow and interception relative to gross precipitation

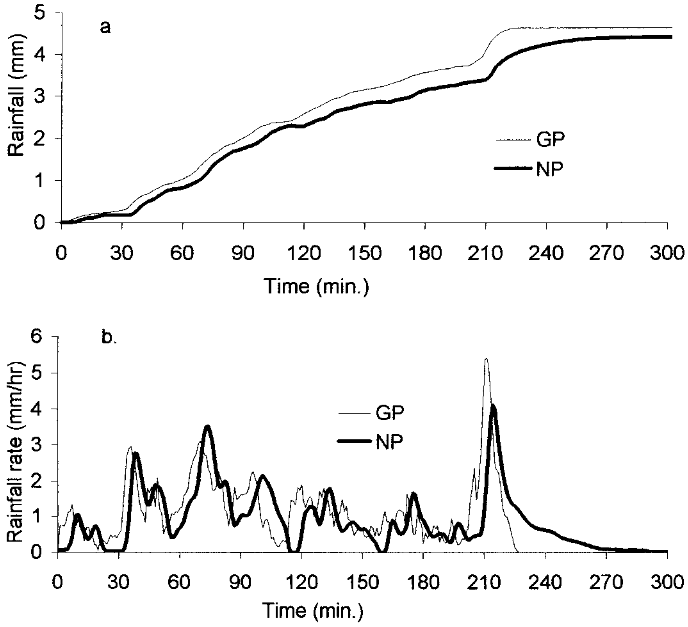

Figure 5. Rainfall hydrograph for the oak tree, showing gross precipitation (GP) and net precipitation (NP). The event occurred at 1623 hours 12 January 1998. (a) The difference between the value on the y-axis is the tree interception. (b) The gross rainfall rate and net rainfall rate

Figure 5 shows the rainfall hyetograph for gross precipitation (above the crown) and net precipitation (below the crown) for the oak tree. The event began at 1623 hours on 12 January 1998 and lasted about 5 h. Several characteristics are seen in the cumulative precipitation plot in Figure 5a. Gross precipitation and net precipitation differ in magnitude. That the two lines are not parallel indicates that interception rates are not constant but change dynamically during the event. After rainfall stopped, net precipitation from crown surface drip and stemflow continued for 75 min. The interception loss was the difference between total gross and total net precipitation after throughfall and stemflow ceased. Crown interception did not reduce the net precipitation peak rate significantly, but delayed the peak by about 10 min (Figure 5b). This delay would also result in a delay in peak runoff from a storm.

Cumulative rainfall, rainfall rate and rainfall duration. The field data (rainfall, throughfall, and stemflow) were analysed statistically at the event scale for the pear and oak trees. Cumulative rainfall had a major impact on throughfall and stemflow yield. The linear relationship between gross precipitation and throughfall is shown in Figure 6 for both the oak and pear trees. Throughfall accounts for approximately 77% and 58% of gross precipitation on to the pear and oak trees, based on the regression analysis of all the measured throughfall data, respectively (Figure 6a and b). For some events less than 1·5 mm, the relationship between throughfall and gross precipitation was less linear (Figure 6c and d). This variability reflects differences in crown wetness at the onset on each rainfall event. For these small rainfall events, most throughfall is from rainfall drops that pass directly through gaps in crown (free throughfall). If the crown surface is wet when rainfall begins, however, the crown drip will be larger than if the crown surface is dry when rainfall begins. If the crown is dry, crown surface storage is a large fraction of gross precipitation. The relatively wide range of throughfall to rainfall ratios observed in the oak and pear trees was caused by both carryover of crown surface moisture variation between events and wind affects. The wind shakes the tree, breaking the temporary surface storage equilibrium and causing drip or flow down along the stem surface. In the rainy season, heavy fog was associated with most small events. Water storage contributed by crown fog

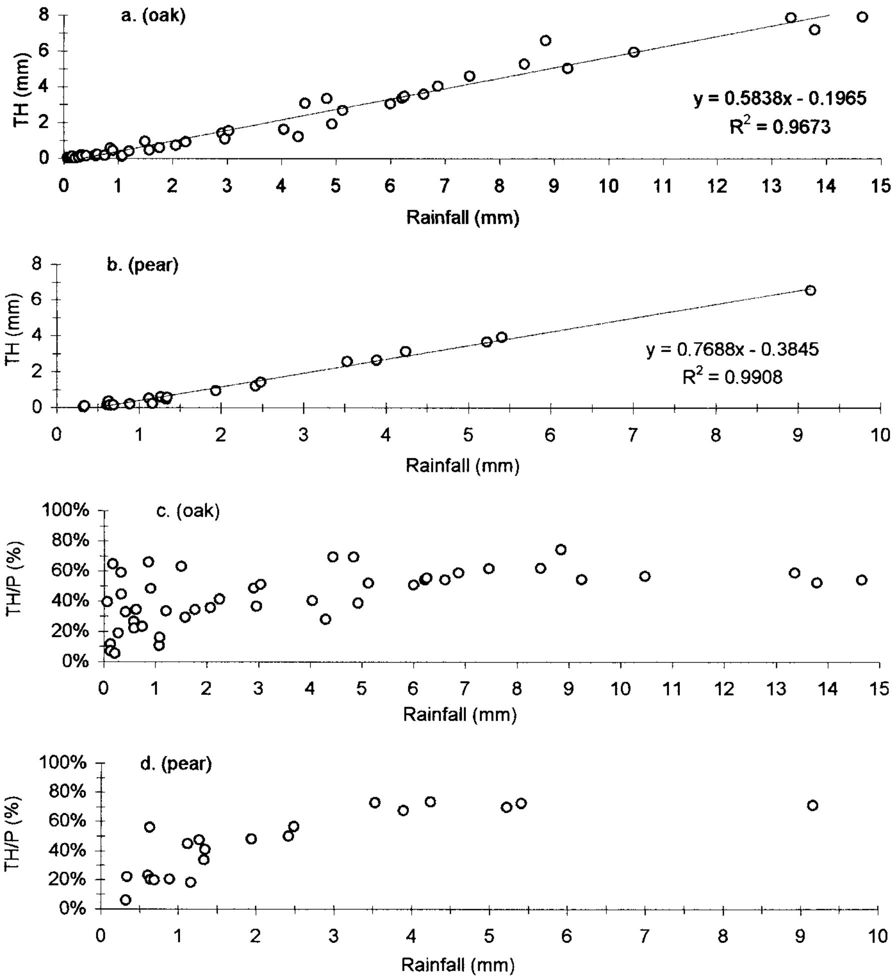

Figure 6. The relationship between total rainfall (P) and throughfall (TH). (a) The relationship between rainfall and throughfall for oak tree. (b) The relationship between rainfall and throughfall for pear tree. (c) The relationship between rainfall and relative throughfall for oak tree. (d) The relationship between rainfall and relative throughfall for pear tree

interception reduced the amount of precipitation required to saturate the crown surface. Even when the rainfall depth was small, the TH/rainfall ratio varied widely. This was because the previous event had saturated the crown surface. The high relative humidity and lower vapour pressure deficit during the time intervals between events limited evaporation losses from crown surfaces. Fog interception was observed in the experiments, but it was not measured in this field study. Although fog deposition is an important precipitation source in some environments, e.g., up to 71% of annual precipitation in cloud forests (Gordon *et al.*, 1994), it has a small effect on annual precipitation at our site. Fog deposition is not associated with the large storms that produce most of the annual precipitation in this climate system.

Crown surface storage capacity. Theoretically, crown drip occurs when surface storage exceeds the surface storage capacity. However, wind blowing the tree canopy and raindrops hitting the leaves and branches can cause crown drip to occur before storage capacity is reached. Crown drip increases with surface storage and rainfall intensity (Massman, 1980; Whelan and Anderson, 1996). Gap fraction and crown surface storage capacity values have been estimated based on measured throughfall and gross precipitation data (Rutter

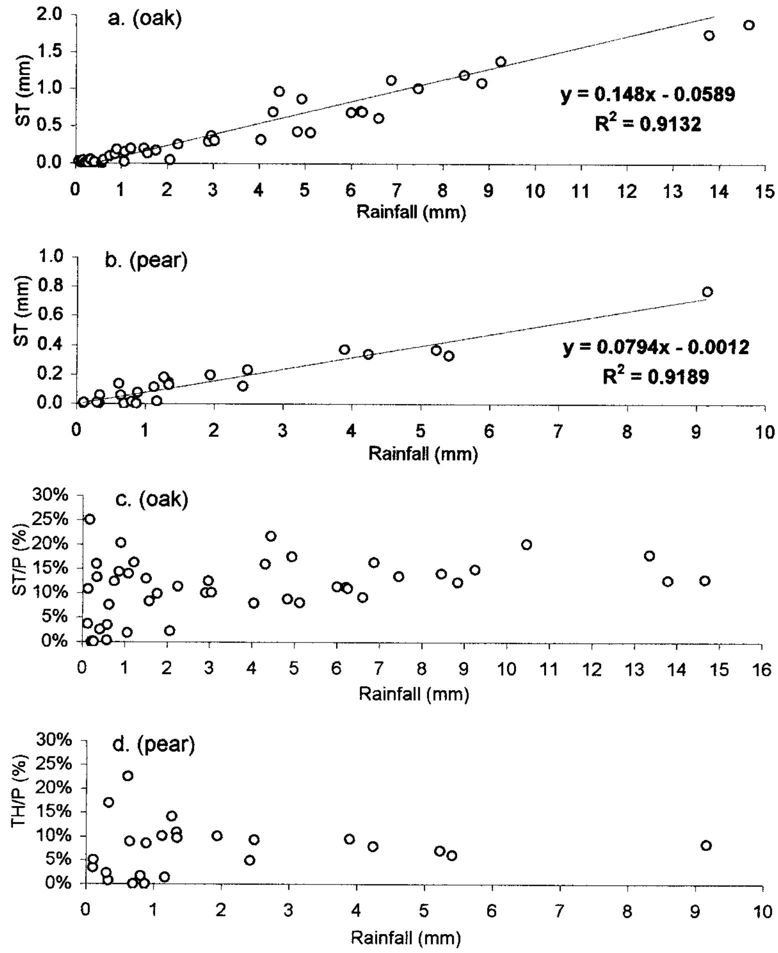

Figure 7. The relationship between total rainfall (*P*) and stemflow (*ST*). (a) The relationship between rainfall and stemflow for the oak tree. (b) The relationship between rainfall and stemflow for the pear tree. (c) The relationship between rainfall and relative stemflow for the oak tree. (d) The relationship between rainfall and relative stemflow for the pear tree

et al., 1971; Gash and Morton, 1978; Kirby *et al.*, 1991). On a plot of the throughfall versus the rainfall data, the slope of the lower envelope line results from small rainfall events and corresponds to the fraction of free throughfall (gap fraction). The gap fraction is 0·6 for the pear tree and 0·3 for the oak tree. The interception point of the gross precipitation and upper envelope line results from larger rainfall events when evaporation is minimal. This value corresponds to crown surface storage capacity (Rutter *et al.*, 1971). The crown storage capacity is estimated to be 1·0 mm for the pear tree and 2·0 mm for the oak tree. These values are similar to those reported in the literature. For example, the canopy surface storage was estimated to be 1·26 mm for a *Pinus sylvestris* forest (Llorens, 1997).

Stemflow. Kirby *et al.* (1991) showed that stemflow parameters can be determined from field rainfall and stemflow measurements, assuming a dry canopy at the onset of rainfall. Only a few of our storm data fit these criteria, because of the high frequency of winter storms. We used linear regression analysis to show an average relationship between precipitation and stemflow for these events, which is seen in Figure 7 for both oak and pear trees. Stemflow was about 15% of gross precipitation on the oak tree (Figure 7a) and 8% of gross precipitation on the pear tree (Figure 7b). This linear relationship was weak for small events. The

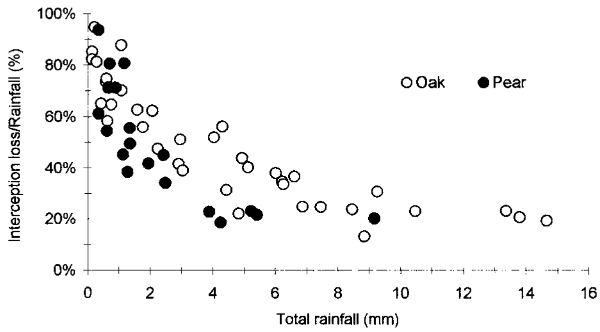

Figure 8. The relationship between relative interception loss and rainfall for the oak and pear tree

crown surface detention storage must fill before stemflow occurs. For a small event (total rainfall, hereafter), stemflow was controlled by the antecedent moisture or water storage conditions of the crown surface. If the surface was saturated, the magnitude of stemflow depended on the amount of rainfall. Otherwise, rainfall is held by the crown surface owing to the surface detention storage. This accounts for the widely varying ratio of stemflow to rainfall in Figure 7(c and d). When the amount of rainfall in the event was greater than the crown surface saturation storage, stemflow was proportional to rainfall (Figure 7c and d).

Because evaporation was limited during and immediately after rainfall stops at our study site, crown storage is the major component of interception loss. For both trees, total interception loss increased with increasing rainfall depth, but relative interception loss (the ratio of interception loss to rainfall) decreased with increasing rainfall (Figure 8). This ratio decreased owing to a limit in crown surface storage, which was controlled largely by tree architecture. For small rainfall events, most of the intercepted water wetted the crown surface and later contributed to evaporation, but the surface water stored on the wetted crown surfaces was less than the saturation storage capacity, thus both stemflow and canopy drip were limited. These small events yield relatively high ratios of interception loss to gross precipitation. For a large event, however, the canopy can only hold a small proportion of the precipitation. Consequently, the percentage interception loss decreased with increasing gross precipitation. The pattern of interception/rainfall ratio to gross precipitation for the pear and oak trees was similar to the pattern observed for a *Pinus sylvestris* forest in Spain (Llorens *et al.*, 1997).

In summary, interception loss for the pear tree on average was 15%. Of the 85% that fell to the ground as net precipitation, 91% arrived as throughfall and 9% as stemflow. For the oak tree, interception loss was 27%. Throughfall and stemflow accounted for 80% and 20% of net precipitation, respectively.

Rainfall rate affects both throughfall and stemflow. For the rainfall events, the rainfall rate was determined by dividing the gross precipitation by the rainfall duration. Throughfall generally increased with increasing rainfall rate for the oak tree and the pear tree, but a regression of *TH* on rainfall rate was not statistically significant for either tree at the 95% level. Crown storage can increase very little after the surface has become saturated so gross precipitation contributes mainly to throughfall and stemflow. Lower rainfall rates result in a slower addition of water sources to the crown and this provides an extended time for crown surface saturation to occur. Water travels down the bole, and refills the storage pool after crown drip occurs. When the rainfall rate increases, however, the drip from temporary crown water storage increases, the frequency of refilling and emptying the storage pool increases, and throughfall increases. Increasing the rainfall rate will increase throughfall, but this change is small and variable. Stemflow was less affected by rainfall rate than throughfall in both the oak and pear trees. When the rainfall rate was greater than $1{\cdot}5 \text{ mm h}^{-1}$, there was a trend towards decreased proportion of stemflow for the oak tree. The same pattern was observed for the pear tree when the rainfall rate was greater than $1{\cdot}5 \text{ mm h}^{-1}$. However, they are not statistically significant for either tree.

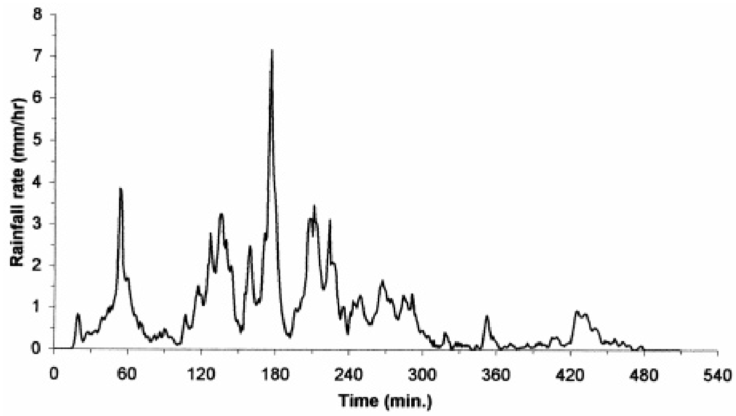

Figure 9. Rainfall hyetograph for a rainfall event that started at 1500 hours 9 January 1998. The rainfall rate varies widely from 0 to 7·2 mm h^{-1}. The average rainfall rate is 0·85 mm h^{-1}

The total amount of rainfall was positively related to rainfall rate ($R^2 = 0{\cdot}52$, $n = 22$, for $P_g < 3{\cdot}0$ mm). This is not surprising because most rainfall occurred at low rates when evaluated at event scale. This means that the effect of rainfall rate must be studied at a time-scale shorter than the event. The rainy season is dominated by frontal precipitation systems. Some large rainfall events occurred at the study site but when these were evaluated over the duration of the event, the rate appeared low because of the extended time period over which low rainfall occurred before and after the event. For example, Figure 9 shows a rainfall event that occurred on 9 January 1998. From the figure, we see that the rainfall rate exceeded 7·0 mm h^{-1} but that the tail was less than 1·0 mm h^{-1}. When we evaluated the mean rainfall rate for the entire event, it was only 0·85 mm h^{-1}.

Rainfall interception losses decreased 3% with increasing rainfall duration, for periods from less than 1 h to less than 2 h, in the oak tree and decreased by 4% with increasing rainfall duration, for periods from less than 1 h to less than 2 h, in the pear tree. When the event lasts longer than 2 h for the pear tree and 4 h for the oak tree, however, interception loss appears to be a constant proportion of gross precipitation.

Wind speed and wind direction. Wind speed affects crown interception. Wind changes the incident angles of rainfall and changes the effective interception area, hence changing the amount of rainfall intercepted by the tree crown. High wind speeds increase evaporation from the wet tree surface, but also increase the rate of drip, which reduces the water available for evaporation. Wind speed and throughfall, however, were not correlated for the oak and pear trees. Throughfall decreased with increasing wind speed at wind speeds greater than 6 km h^{-1}, but stemflow increased with increasing wind speed. Interception losses increase with increasing wind speed for wind speeds greater than 6·0 km h^{-1} and less than 15 km h^{-1}. This dependence was weak for the pear tree because of its architecture. The oak tree was in-leaf and the leaf surfaces provided a large pool for crown surface storage, whereas the pear tree was leafless. With stronger winds, there is potential for more moisture to be available for wind movement and evaporation for the oak tree.

During our 2 years of data collection, wind directions varied from south-west to south-east owing to the geographical setting of the experiment site. The relationship between interception and wind direction was not statistically significant at the 95% level.

Tree species. Interception by the pear and oak tree follow similar responses to rainfall but of different magnitudes. The contribution of gross precipitation to stemflow was more than 15% for the oak tree compared with 8% for the pear tree. This difference is a result of the oak tree's evergreen foliage and tree architecture. During the rainy season the pear tree was leafless. The pear tree had smooth bark and the branches were predominantly vertically (zenith angle less than 45°) orientated and the angle between main branch and sub-branch was small (less than 45°), which reduces the possibility of intercepted water dripping from the crown surface. Instead, the water flows along the smooth barked branches until it converges at the bole. Little water (less than 1 mm) was required to wet this smooth bark surface and water flowed along the branches relatively quickly. This resulted in a high proportion of interception contributing to stemflow. Throughfall was dominated by free throughfall, of which drip from crown surfaces was only a small fraction. No stemflow was observed on the pear tree when rainfall was less than 1·0 mm, except when the previous event had already wet the bark surface. The oak tree's dense leaf crown coverage provided a large pool for intercepted water storage, and throughfall was primarily by crown drip. Most branches on the oak tree were vertically orientated, which also allowed the surface water storage to converge on the bole. The rough bark surface, however, provided a large surface for water storage and also reduced the stemflow rate along the branch. Stemflow for the oak tree was about 15%, significantly greater than for the pear and for stemflow partition coefficients reported by Gash (1979), Sinun *et al.* (1992), and Llorens *et al.* (1997) for natural *Pinus sylvestris* forests (1·8–2·0%). High percentages of stemflow measured in both trees agree with the results of Herwitz (1987) from simulated rainfall under laboratory conditions.

It was surprising that stemflow accounted for such a high proportion of gross precipitation in the oak tree, nearly two times greater than for the pear tree. Both the pear and oak trees had the same crown shape (paraboloid or cone) and the ratio of crown height to crown diameter was similar. The oak leaves, which were orientated (the axis of petiole and tip) more or less vertically, however, created a large interception area to catch the rainfall. This intercepted precipitation flowed along the petiole to the stem, greatly increasing stemflow.

This research has several important consequences for measurement and hydrological modelling. First, our results confirm that some interception coefficients derived from rural forest trees do not apply directly to open-grown trees. To model impacts of large-scale urban tree plantings on interception and runoff more accurately, we need better understanding of these processes in the non-forest setting. Second, architectural features of tree species are important factors controlling the distribution of interception processes. A greater understanding of the relative importance of these features and their characteristics for common tree species will aid modellers and inform resource managers in selecting appropriate trees to maximize the hydrological benefits. Finally, measurement systems similar to the one we describe provide an ideal experiment for determining how tree architecture features influence interception. Different tree species can be evaluated and crowns can be manipulated in a controlled manner in order to test hydrological assumptions.

CONCLUSIONS

Crown rainfall interception is influenced by three factors: characterization and magnitude of the rainfall event, tree species and architecture, and meteorological factors. Rainfall intensity and duration provides the water supply driving the interception process. Tree species and architecture provide the space and routes to store the moisture and control the flow. Temperature, relative humidity, net radiation and wind speed control the rate at which water is removed from crown surface storage. For example, relative interception loss increases with wind speed, crown leaf density and rainfall duration. The time lag between onset of gross precipitation and onset of stemflow and throughfall is larger for the oak tree than for the pear tree. The rough bark surface and the leaf density on the oak tree accounts for this longer lag. Both time lags and reduced magnitude of gross precipitation to net precipitation indicate that the crown does provide a positive and mitigating influence towards urban runoff control.

The function of crown rainfall interception processes is different when considering scale and short time periods. Llorens *et al.* (1997) indicated that the event-scale yielded the best results for predicting interception because the duration and the magnitude of the event had greatest effect on interception. Although this is true for water budget and for interception loss prediction, nonetheless a finer temporal scale may be needed for better understanding of the processes. At our study site, where winter frontal systems dominate precipitation, wind direction did not show specific relationships with interception except as indicated by the source direction of rainfall.

About 15% of gross precipitation was lost as a result of crown interception for the pear tree and more than 27% for the oak tree. Relative interception losses decreased with increasing rainfall magnitude and increased with increasing rainfall duration. Rainfall interception loss was positively correlated to wind speed because higher wind speed corresponds with higher potential to remove the moisture from the tree surface.

Throughfall accounted for 77% of gross precipitation for the pear tree and 58% for the oak tree. The difference reflects differences in tree architecture. The leafless pear tree had a larger gap coefficient that corresponded to greater free throughfall. Crown surface water storage was limited to stem surfaces. During the rainy season the oak tree was in-leaf. This produced a larger additional water storage pool than the pear's stem surface. Water is stored temporarily on the crown surface and redistribution of this storage reduced throughfall and increased stem flow.

Stemflow accounted for 8% of gross precipitation for the pear tree and 15% for the oak tree. These values are larger than those from other interception studies reported from natural forests. Unlike the situation in natural forests where tree crowns overlap, for these isolated trees wind-associated rain drip can directly intercept the tree trunk. This interception brought relatively higher moisture levels to the stem than those observed in natural forests. Another reason is that most branches on both trees were vertically oriented. This architecture feature accelerated convergence of stemflow and reduced stem drip.

The winter domain precipitation climate at our study site limited our opportunities for collecting interception data during non-winter seasons. The solar radiation and temperatures are low during the winter, which limits the potential evaporation of tree surface water storage. In the rainy season, the pear tree was leafless, therefore the total surface water storage is entirely from the stem surfaces. So the actual interception losses of pear and oak trees may be higher in places that have frequent summer rainfall and warm, sunny conditions.

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