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Rainfall interception by a *Pinus sylvestris* forest patch overgrown in a Mediterranean mountainous abandoned area I. Monitoring design and results down to the event scale

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Abstract

Monitoring (in 5 min steps) of precipitation, throughfall, stemflow and bulk canopy wetness, and also weather conditions and soil moisture, was carried out from July 1993 to December 1995, in a *Pinus sylvestris* forest patch located in a Mediterranean mountainous former agricultural basin subject to spontaneous change from pasture to forest. Throughfall collectors were designed to obtain hydrologically representative data and they consist of nine troughs with a total catchment area of 9 m^2. The bulk interception rate measured after 30 months of monitoring was about 24%. Relative interception was irregular and decreased with the magnitude of the event; it was at least 15% for events of more than 20 mm.

Multivariate analysis of the events demonstrates that their characteristics can be simplified in two main factors which respectively represent the duration of the event and its magnitude. The magnitude of the event biases the characterization because of the non-linearity of the rainfall–interception relationship. Long events do not produce higher interception rates than shorter ones because of the occurrence of low vapour pressure deficits during the former. In atmospheric dry conditions the rainfall intensity provides the main control on interception rates. © 1997 Elsevier Science B.V.

Keywords: *Pinus sylvestris*; Rainfall-interception relationship; Precipitation; Throughfall; Rainfall intensity

1. Introduction

There is increasing agreement among researchers that forest land cover releases higher water losses to the atmosphere than grassland (Bosch and Hewlett, 1982) and that this is the result of increased rainfall interception (Calder, 1990). Nevertheless, most of the

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studies were conducted in temperate humid areas, where low evaporation rates are efficient because of the length of time for which the canopy is wet (Calder and Newson, 1979), or because of the frequent wetting and drying of the canopy produced by small intermittent rainfall (Rutter, 1975).

Interception rates measured in Mediterranean areas seem to be rather less consistent (Humbert and Najjar, 1992). There are several studies on interception in these areas (Rapp and Ibrahim, 1978; Bellot, 1989; Alvera, 1990; Piñol et al., 1991; Duwig, 1994; Moreno, 1994; Domingo et al., 1994), but most of them focused on nutrient cycling (water quality), and therefore lack an appropriate design to represent spatial and temporal water quantity phenomena. Knowledge of the interception processes in Mediterranean areas threatened by environmental changes and with wide ranges of meteorological conditions is of major scientific and applied interest.

The aim of this paper is to introduce a detailed experiment designed to provide continuous monitoring of water fluxes in a pine forest patch located in a Mediterranean mountainous area subject to spontaneous overgrowth of forest, within the framework of a small research catchment. The results obtained after 30 months of monitoring are presented, and special attention is paid to the analysis of the different kinds of event observed.

2. Study area

The Cal Parisa basin (36 ha), located in the Vallcebre experimental catchment (Eastern Pyrenees, Spain) at 1400 m above mean sea-level, was selected as representative of abandoned agricultural fields in Mediterranean mountainous areas (Llorens and Gallart, 1992). The climate is Mediterranean mountainous, with a mean annual precipitation of 850 mm and a mean annual temperature of about 9°C.

Since 1989, the hydrological response of the more man-modified sub-basin has been studied to analyse the role of land use changes in water and land conservation. The main geoecological implications of the earlier agricultural land use were marked modifications to the vegetation cover, topography and drainage net, with significant impact on geomorphological and hydrological behaviour (Llorens et al., 1992; Gallart et al., 1994). After the abandonment of agricultural fields, the forested area of the basin has increased from 5% to 25% in the last 20 years. Spontaneous reafforestation seems to be the main geoecological change that may modify the hydrological response of the basin (Llorens, 1993).

3. Monitoring design

Since 1989, the Cal Parisa basin has been provided with a pluviometric and hydrological network consisting of four rain recorders, two hydrometric stations at each sub-basin outlet and one meteorological station (Llorens and Gallart, 1992).

3.1. *Characteristics of forest patch*

Since July 1993 the 'Ramon Poch' experimental plot was instrumented to evaluate forest water balance. This plot of 198 m^2 is covered by a monospecific *Pinus sylvestris* stand with poor understorey. Stand density is about 2400 stems ha^{-1}. Mean diameter at breast height (DBH) of trees is 14.3 cm with a variation coefficient of 50%. Mean height is 10 m with a variation coefficient of 28%, and the mean age of the trees is 33 years with a variation coefficient of 18%. This plot is taken as representative of small patches of pines overgrown in areas marginal to the agriculture, which were abandoned in the first half of the century. Border effects are therefore to be taken into account, although they are considered peculiar to the spontaneous afforestation process (Fig. 1).

3.2. *Instruments setting*

A data logger stores the readings for the following variables at 5 min steps.

3.2.1. *Throughfall*

Three sets of three trough collectors, each with a surface area of about 1 m^2, collect the throughfall, which is then measured by three tipping buckets. The collectors are made of galvanized steel sheet, and measure 385 cm × 27 cm. The cross-section of the channel is a V shape, with a depth of 45 cm, to prevent loss from splashing. The collectors are raised about 100 cm above the ground on a steel structure, to prevent splashing from the ground. They are inclined at about 15° to the horizontal to ensure rapid flow to the tipping buckets. These buckets are made of aluminium sheet and are V shaped. The volume of each bucket is about 90 ml, and the arrangement allows a resolution of 0.03 mm for each set. The dynamic calibration of tipping bucket devices is considered in a following section.

Falling necromass (needles and small branches) collected in each set of troughs was weighed at weekly intervals. Spatial differences in necromass weight were considered as an indicator of the spatial variations of the leaf area above each trough.

3.2.2. *Stemflow*

The stemflow received by seven trees is also measured in three tipping buckets of the same design. The stemflow collectors are polyurethane foam rings sealed with silicone rubber, forming a watertight junction between the ring and the tree bark.

3.2.3. *Canopy wetness sensors*

Six wetness sensors are distributed within the canopy. These sensors consist of strips of parallel electrical wire, of 5 cm length and 3 mm width. The insulation was removed from one side of the cable. The signal from these sensors is based on their electrical conductivity, and they were calibrated to read 'wet' when placed in contact with one drop of tap water.

3.2.4. *Rainfall*

One large rainfall recorder (1 m^2 surface), with the same characteristics as the throughfall collectors was placed outside the forest area, together with a tipping bucket. One conventional funnel rain recorder (200 cm^2) with a resolution of 0.2 mm was placed at the ground level.

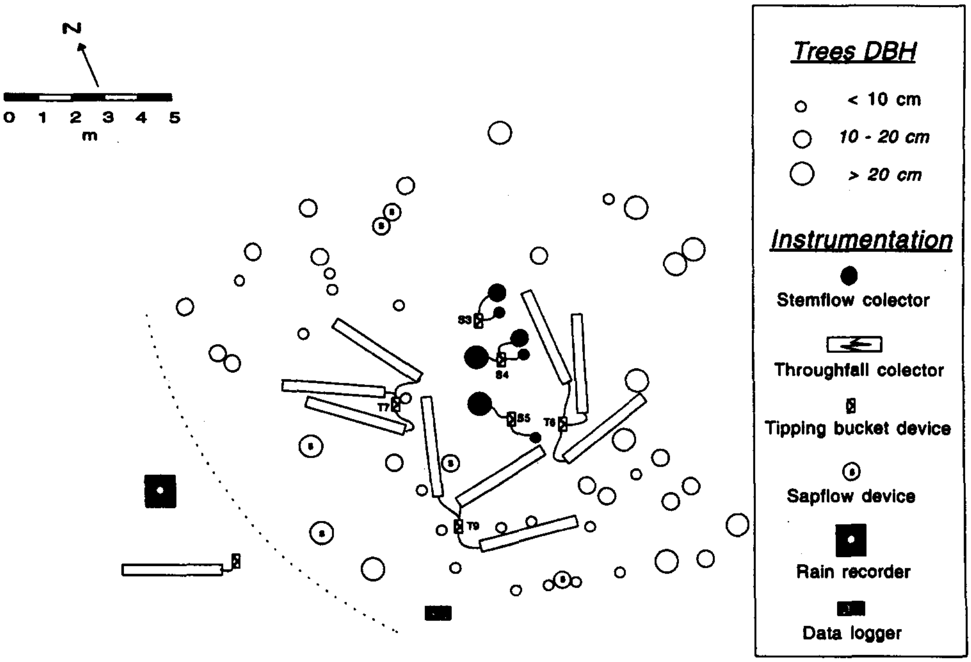

Fig. 1. General arrangement of the experimental plot for the study of forest interception fluxes at the Cal Parisa basin (Eastern Pyrenees, Spain).

3.3. Complementary instruments

Soil moisture profiles were instrumented both inside and outside the forest area with Time Domain Reflectometry (TDR) sensors at 0–20, 20–40, 40–60 and 60–80 cm below the soil surface; readings were taken weekly (Rabadà and Gallart, 1993). These data were complemented with grassland evapotranspiration data obtained from a Bowen ratio energy balance station situated outside the forested area from March 1994 onwards, and by monitoring tree transpiration using Granier's sap flow measurement technique (Granier, 1985) from July 1994 onwards (Llorens and Poch, 1994).

3.4. Dynamic calibration of tipping buckets

A dynamic calibration of the throughfall tipping buckets was performed to obtain both high resolution and accuracy (Calder and Kidd, 1978). High rainfall intensity events, which imply large volumes of water in a short time, suppose a failure of the tipping buckets to measure accurately if we applied a static calibration. This kind of calibration is absolutely necessary to give accurate interception loss results because the interception is calculated as differences between rainfall and throughfall (Shuttleworth, 1989).

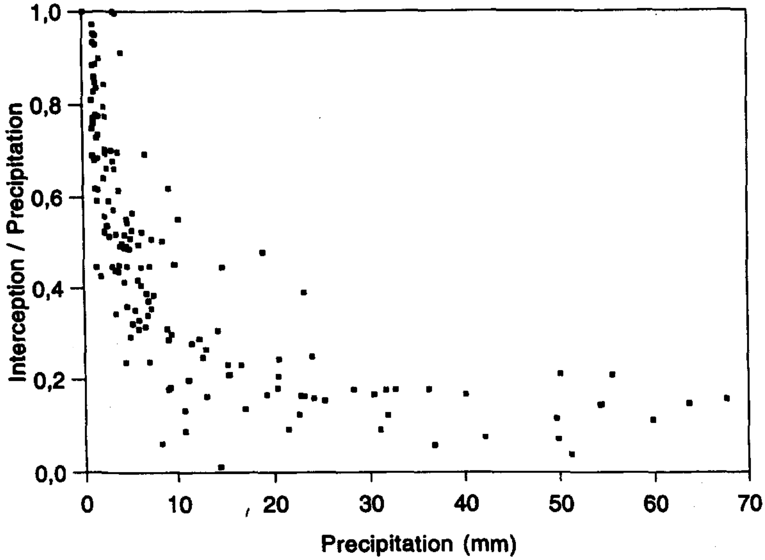

Fig. 2. Relationship between relative interception and precipitation at the event scale.

4. Results

The results presented here include data from July 1993 to December 1995, containing 152 events with a total bulk rainfall of 1825 mm. The experimental design allows data analysis at several temporal scales but only the results at the daily, weekly and event scales are presented here.

During the study period two large and intense rainfall events, with more than 100 mm of bulk rainfall, occurred. These two events have a return period of about 10 years and showed an important spatial variability, up to 9%, of bulk rainfall. This variability implies an uncertainty in the calculated interception; for example, for an event in November 1994, with a mean rainfall of 130.5 mm, the measured interception varied between –9.0 mm and 24.9 mm depending on the rain recorder selected, although these rain recorders are only a few tens of meters apart. For this reason, these two events are not considered in the present analysis.

Snow events were eliminated from the analysis to avoid errors introduced by the low accuracy in snowfall measurement. Field observation of the occurrence of some snow patches covering the soil was used to eliminate the data of the antecedent week.

The main characteristics of the rainfall–interception relationship at the event scale are: (1) the *Pinus sylvestris* patch intercepted about 24% of the bulk precipitation; (2) interception depths increased with precipitation, following a curve with positive but decreasing slope, without stabilization for the highest events (see Fig. 8, below); (3) relative interception decreased from more than 50% of bulk rainfall for events of less than 8 mm to about 15% for events greater than 20 mm, and remained constant for greater events (Fig. 2); (4) there is an important range of interception depths for all the amplitude of the rainfall depths (see Fig. 8, below). There are several aspects of the results that deserve more detailed analysis, as follows.

4.1. *Spatial variability of throughfall and stemflow*

4.1.1. *Validity of the design of troughs*

The effect of the geometry of throughfall collectors on measurement accuracy is unclear (Neal, 1990), but the kind of trough used here were constructed to minimize two of the effects influencing trough catch cited by Neal (1990), namely the splash-off and the splash-on. The third aspect that affects collection, the aerodynamic behaviour of the troughs, remains to be tested.

A comparison of daily rainfall collected by the ground level funnel rain recorder and by the trough rain collector, during 218 rainy days (January 1994–December 1995) with a total mean rainfall of 1498.5 mm, ranging from 0.1 mm to 59.3 mm, shows that absolute differences were slight. The total rainfall measured by the funnel was 71 mm greater than that measured by the trough. This difference represents 5% of the rainfall collected. The correlation coefficient is good and the slope of regression is not different from unity.

Uncertainty of measured bulk rainfall at the event scale for the events between 1 mm and 70 mm is lower than 5%, and this figure is reduced to 3% for events between 30 mm and 70 mm. Uncertainty of measured throughfall at the same scale for events between 30 mm and 70 mm is about 3%. The uncertainties in the measurement of bulk rainfall and throughfall imply an important uncertainty in the calculation of interception, because it is the smaller term of the balance, and this uncertainty for events between 30 mm and 70 mm yields values up to 30%.

4.1.2. *Spatial variability*

The three sets of three collectors give a total catchment area of about 9 m × 1 m, which represents the same area as that of 9 × 50 rain gauges of 200 cm^2. We can therefore assume that this monitoring design allows an important reduction of the spatial variability of the net rainfall at a scale smaller than 1 m.

The larger-scale spatial variability of throughfall data at the event scale is represented in Fig. 3. The figure compares one set of throughfall collectors (T7) with the two others (T6 and T9). Differences in catch between pairs of collectors sets were 6% between T6 and T9 and about 12% between T6 + T9 and T7. Considering throughfall collectors T6 and T9 as belonging to the same population, the correlation between T6 + T9 and T7 would be statistically significant at the 0.1% level ($r = 0.982$ and $N = 289$).

The variability of throughfall decreases suddenly for the events with more than 5 mm of bulk rainfall, and the coefficient of variation for greater events tends asymptotically to less than 5% (Fig. 4); this trend is the same as that observed by other workers (Aussenac, 1970; Loustau et al., 1992).

This difference in catch between Troughs T7 and the other two sets of collectors is determined by the spatial distribution of the density of the forest canopy at the 5 m scale, Troughs T7 being installed below a relative clearing. Differences in necromass collected between T6 and T9 (about 7%) are also lower than the differences of these sets of collectors with T7 (about 25%).

There was marked variation in stemflow at the event scale (Fig. 5). In this case, the main factor that affects stemflow measurement is the loss of accuracy when very small water

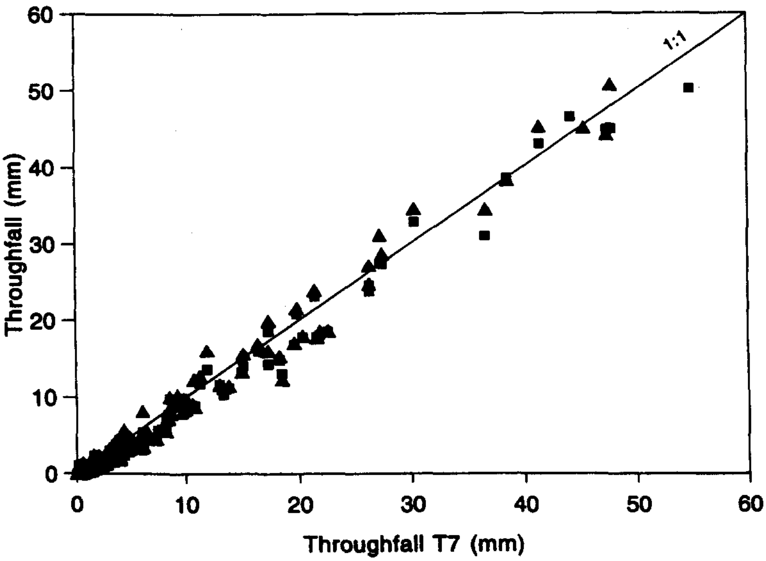

Fig. 3. Comparison among throughfall depths collected in troughs sets T6 (■) and T9 (▲) vs. T7.

volumes are measured. Mean stemflow represents only 1.3% of the bulk rainfall (1.7% of the net rainfall), these figures being small enough to exemplify that a small error in stemflow measurement clearly affects its variability, but its role in interception measurement is here secondary.

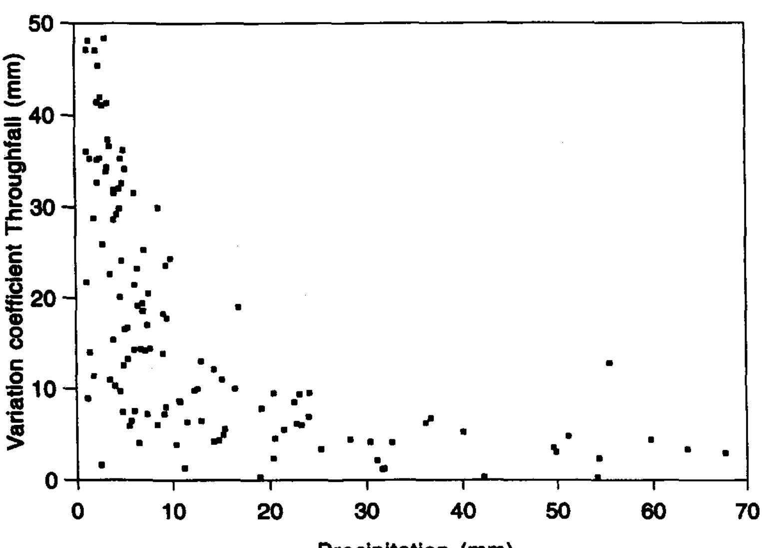

Fig. 4. Decline of spatial variation coefficient of throughfall with increasing event rainfall depth.

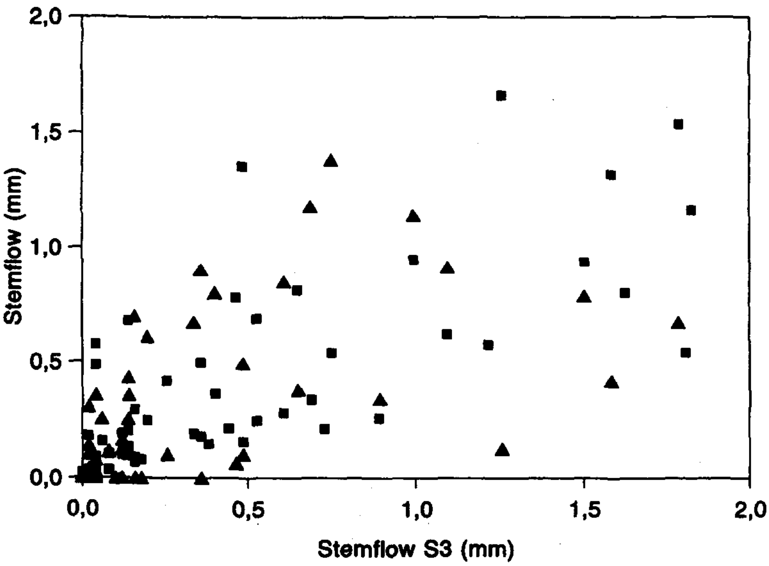

Fig. 5. Comparison among stemflow depths collected by sets S4 (■) and S5 (▲) vs. S3.

4.2. *The rainfall–interception relationship at different temporal scales*

The data obtained at the experimental plot allow the comparison between bulk rainfall and interception at different temporal scales. The time units for the different temporal scales were decided as follows:

1. the daily scale included readings from 00:00 to 23:55 h.
2. The weekly scale included readings during 7 days.
3. The event scale included periods with more than 1 mm of bulk rainfall, separated by periods characterized by bulk rainfall, throughfall and stemflow equal to zero and also canopy wetness lower than 66.6%. The events excluded from this analysis number 632, with a total amount of bulk rainfall of 31.5 mm (1.7% of the total bulk rainfall) and an interception rate of 32.5%.

The purpose of this comparison is to determine whether the rainfall–interception relationship is constant at different temporal scales. This implies a parallel comparison between the event scale, which represents the scale of the hydrological processes, the daily scale, which represents the scale of routine rainfall records, and the weekly scale, which represents the common scale of interception experiments.

Fig. 6 presents the rainfall–interception relationship for the three temporal scales studied. To simplify the analysis a potential regression was adjusted for each relationship. Although this kind of adjustment does not represent the best fit, it is used to compare the relationships statistically.

This figure shows that there are important differences in interception depths at the temporal scales analysed for the same range of precipitation. At the weekly scale the

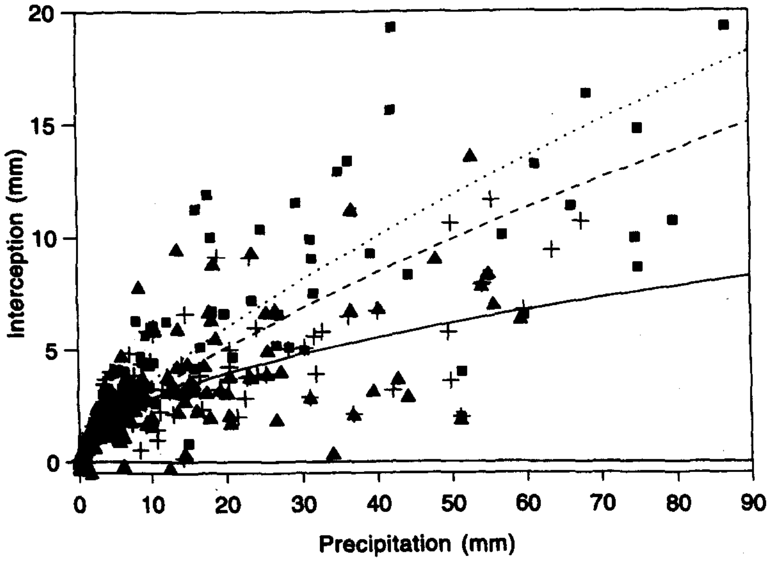

Fig. 6. Relationships between interception and rainfall depths for different temporal scales of analysis: weekly scale (■), daily scale (▲) and event scale (+). The potential curves for the weekly scale (· · ·), the daily scale (– – –) and the event scale (——) are statistically different.

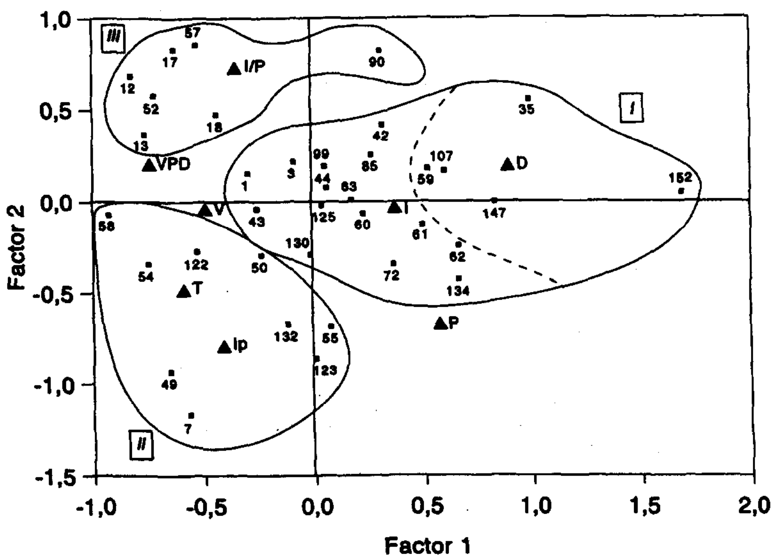

Fig. 7. Distribution of rainfall and other weather variables together with the studied events in the plane defined by the first two axes resulting from a principal component analysis. D is duration, P is precipitation, I is interception, I_p is rainfall intensity, T is air temperature, V is wind velocity, VPD is water vapour pressure deficit, and I/P is relative interception. I, II and III represent the classes of events.

interception depths for the same range of rainfall are higher, owing to the sum of small events; for the 74 weeks studied with rainfall higher than 1 mm, only 39% of the weeks have one unique event. For this reason, the trend of the relationship is more linear than at the event scale.

Of the 152 events studied, 134 had a duration shorter than 24 h, but 54 of these occurred during the night, as only 80 events coincided with one calendar day. The daily scale, even if it cuts some of the events, showed more similarity with the event scale because events are frequently shorter than one calendar day.

The statistics of the three relationships shows that: (1) at all three time scales the potential regressions are statistically significant at the 1% level; (2) the three exponents are significantly different from unity, indicating that the curvature of the graph is significant; (3) the comparison between the three different rainfall–interception potential curves performed with the Student's t-test indicates that the exponents are significantly different for each pair compared (0.1% confidence level). These analyses allow us to state that the rainfall–interception relationship changes with the temporal scale, and that data obtained at one scale cannot be directly transferred to a shorter scale.

4.3. The interception process at the event scale

Fig. 7 shows the distribution of 36 events of more than 5 mm rainfall on the plane defined by the two first axes of a multivariate analysis (principal component analysis) performed with the variables indicated in the graph. These two first axes explain 57.5% of the total correlation. As this total correlation is low, it is necesary to consider also a third axis, not represented in the figure, the three first axes explaining 77.5% of the total correlation.

The first axis is defined by the opposition of the meteorological variables such as air temperature (T), wind velocity (V) and water vapour pressure deficit (VPD) versus the total duration of the event (D). This first axis explains 33.5% of the correlation and represents an axis that differentiates short dry events from long wet ones. The second axis, which explains 24% of the correlation, is determined by the opposition between the magnitude of the event (P) and its intensity (I_p) versus the relative interception (I/P), and opposes large intense events to small gentle ones. The third axis, which explains 20% of the correlation, is determined by the interception depth (I).

As the non-linearity of the relationship between rainfall and interception gives an important role to the magnitude of the event in the classification, a multivariate classification of the events was made after a division of events into two groups depending on the magnitude of the bulk rainfall (events with bulk rainfall greater or smaller than 40 mm). The results produced three main classes of event, whose characteristics are summarized in Table 1:

- Class I: Long events with low rainfall intensities and wet atmospheric conditions. These events produce low interception rates, with a mean of about 15%. They represent 62% of the bulk rainfall and 57% of the interception loss of the 36 classified events. In this group there is the possibility that some of the events (numbers 35, 147 and 152) were partially of snow. This group of events could be divided into two subgroups depending on the duration of the bulk rainfall (Class Ia for very long events and Class Ib for those of medium duration).

Table 1

Rainfall, interception and meteorological data of the events used for the principal component analysis; the classes correspond to those in Fig. 7

Class	Event	D (h)	T (°C)	VPD (mbar)	V (m s^{-1})	P (mm)	I_p (mm h^{-1})	I (mm)	I/P
Ia	35	56.0	1.2	0.02	0.4	22.8	0.4	3.8	0.17
Ia	59	30.1	6.6	0.30	0.5	31.7	1.1	5.6	0.18
Ia	107	44.7	8.7	0.22	0.8	32.7	0.7	5.8	0.18
Ia	147	31.1	1.3	0.00	0.6	49.9	1.6	3.6	0.07
Ia	152	75.8	1.3	0.00	0.5	63.6	0.8	9.4	0.15
Mean		47.5	3.8	0.11	0.6	40.2	0.9	5.6	0.15
Ib	1	10.0	10.2	1.14	1.0	16.6	1.7	3.8	0.23
Ib	3	12.5	8.0	0.73	0.7	10.9	0.9	1.0	0.09
Ib	42	22.1	3.4	0.13	0.5	8.4	0.4	0.5	0.06
Ib	43	5.8	6.2	0.79	1.3	25.3	4.3	3.9	0.15
Ib	44	13.9	6.1	0.08	1.2	21.5	1.5	2.0	0.09
Ib	60	18.3	7.8	0.24	0.9	31.9	1.7	3.9	0.12
Ib	61	32.2	8.7	0.34	1.4	50.1	1.6	10.6	0.21
Ib	62	31.1	10.6	0.35	0.7	55.6	1.8	11.6	0.21
Ib	63	18.3	9.7	0.19	0.6	22.6	1.2	2.8	0.12
Ib	72	30.3	8.1	0.48	2.2	67.7	2.2	10.7	0.16
Ib	85	17.7	2.2	0.31	1.2	28.3	1.6	5.0	0.18
Ib	99	12.1	6.5	0.49	0.9	20.6	1.7	5.0	0.24
Ib	125	17.4	13.1	0.10	0.7	24.2	1.4	3.9	0.16
Ib	130	10.9	11.6	0.04	0.9	31.1	2.9	2.9	0.09
Ib	134	32.4	11.4	0.00	0.7	59.8	1.8	6.8	0.11
Mean		19.0	8.2	0.36	1.0	31.6	1.8	5.0	0.15
II	7	4.2	11.7	2.04	1.2	54.4	13.0	7.9	0.15
II	49	3.5	14.1	1.07	1.1	36.8	10.5	2.1	0.06
II	50	9.3	13.0	1.09	1.0	36.2	3.9	6.5	0.18
II	58	2.3	8.9	1.78	2.0	13.1	5.8	2.1	0.16
II	122	3.3	12.2	0.76	1.1	19.3	5.8	3.2	0.17
II	123	7.6	12.9	0.40	0.9	54.2	7.1	7.9	0.15
II	132	6.3	11.9	0.36	0.7	42.2	6.7	3.2	0.08
Mean		5.2	12.1	1.07	1.1	36.6	7.6	4.7	0.13
III	12	16.4	13.8	3.26	0.9	10.0	0.6	4.5	0.45
III	13	8.6	11.7	3.24	0.9	14.3	1.7	4.4	0.31
III	17	5.0	4.0	2.17	1.3	7.6	1.5	3.9	0.52
III	18	13.5	7.5	2.58	1.4	23.3	1.7	9.1	0.39
III	52	6.8	13.6	1.14	1.4	9.5	1.4	5.9	0.62
III	57	9.3	11.0	1.00	0.9	7.0	0.8	4.8	0.69
III	90	26.8	0.6	0.33	1.4	19.0	0.7	9.1	0.48
Mean		12.3	8.9	1.96	1.2	12.9	1.2	6.0	0.49

- Class II: Short events with high rainfall intensities and dry atmospheric conditions. These events produce the lowest interception rates, with a mean of about 13%. They represent 24% of the bulk rainfall and 18% of the interception loss of the classified events.
- Class III: Medium events with low rainfall intensities and very dry atmospheric conditions. These events produce the highest interception rates, with a mean of

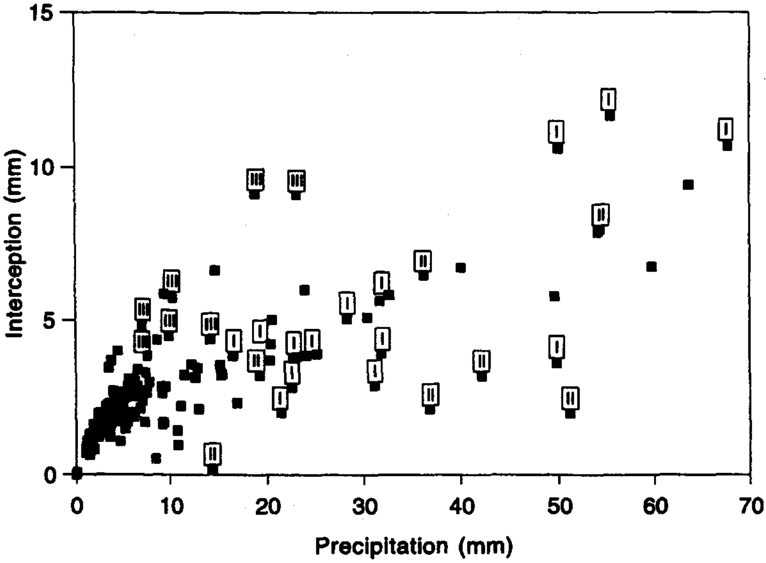

Fig. 8. Relationship between interception and rainfall depths at the event scale. I, II and III represent the three classes defined in Fig. 7, and numbers correspond to those in Table 1.

about 49%. They represent 8% of the bulk rainfall but as much as 23% of the interception loss of the classified events.

The insertion of these three groups of events in the rainfall–interception relationship at the event scale is shown in Fig. 8. This figure reflects that the classification in three main groups of events is representative of the general trend of the rainfall–interception relationship in the area studied for events with more than 5 mm rainfall.

These groups of events suggest the following:

1. An interception process with similar characteristics to those described in the literature from temperate–humid areas. In this case, interception is moderate owing to the wet atmospheric conditions, and is affected by low evaporation rates that are efficient because of the length of time when the canopy is wet (Class I).
2. Two interception processes with Mediterranean characteristics. Both cases are characterized by dry atmospheric conditions, but the difference in the interception loss is due to the rainfall intensity. In one case (Class II) interception is low owing to the high rainfall intensities, and in the other case (Class III) interception is very high owing to the low rainfall intensities, which lead to active re-evaporation even during rainfall.

This grouping of events does not seem to be influenced by seasonality, because in all the groups there are events from the different rainy seasons (spring, autumn and summer).

5. Discussion

There are few references to interception losses in Mediterranean areas with which to compare the data presented. There are several studies on nutrient cycling by Mediterranean species, but they lack an appropriate hydrological design (Bellot, 1989; Alvera, 1990; Piñol et al., 1991; Moreno, 1994; Domingo et al., 1994). Other studies performed with greater emphasis on hydrological analysis refer to tree species other than *Pinus sylvestris* (Rapp and Ibrahim, 1978; Duwig, 1994). We therefore compare our data with data from the same species of trees but in another climate and with data from other species of trees in the Mediterranean area.

Bulk interception of about 24% obtained in the Cal Parisa experimental plot is comparable, on the one hand, with interception rates obtained in several *Pinus sylvestris* studies in humid–temperate climates (Bodeux, 1954; Aussenac, 1968; Gash and Stewart, 1977; Gash et al., 1980; Johnson, 1991). On the other hand, it is also comparable with interception rates from other species in Mediterranean conditions (*Quercus suber* and *Arbutus unedo* in the study by Duwig (1994) and *Pinus pinea* in that by Rapp and Ibrahim (1978)). This interception rate is nevertheless much higher than that obtained in other experiments in Mediterranean environments for different species (Bellot, 1989; Alvera, 1990; Domingo et al., 1994; Piñol et al., 1991; Moreno, 1994).

The individualization of events is a complex exercise subject to some degree of ambiguity and subjectivity. To take these decisions we used not only rainfall information but also canopy wetness data because a short interruption of rainfall is not sufficient to indicate the start of a new event if the canopy remains close to saturation. The inconveniences of this choice are that our results cannot be compared directly with other observations that lack this kind of information, and that the inverse relationship between duration of the event and air dryness becomes reinforced. Overlooking these ambiguities, the functioning of the interception processes is best understood at the event scale. Data obtained at a longer (weekly) scale are only adequate to assess the total interception loss but cannot be extrapolated to a shorter scale, as is usually needed for hydrological models. Mediterranean type events differ from temperate–humid ones in the atmospheric evaporative demand, which plays an important role during events with low rainfall intensities, allowing extreme interception losses, but does not have major importance in intense showers during typical Mediterranean short events. These results emphasize some aspects in the rainfall–interception relationship that suggest the requirement of a more detailed temporal analysis of water fluxes to characterize the interception process in Mediterranean mountainous conditions.

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