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Surface and subsurface flow in eucalyptus plantations in north-central Portugal

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Abstract: In the Baixo Vouga region of north-central Portugal, forests occupy half of the territory, of which two thirds are Eucalypts plantations. The hydrological implications of this large-scale introduction of eucalypt are unknown and the aim of this exploratory study, realized in the Caramulo Mountains, was to describe overland flow (OLF), subsurface flow (SSF) and stream flow (Q) in a catchment dominated by Eucalyptus plantations. The main conclusions are that annual OLF rate is low, spatially heterogeneous between 0.1% and 6% and concentrated during the wet season as saturation excess, particularly as return flow. Infiltration-excess OLF due to the strong soil water repellence (SWR) is dominant during dry season, but produces residual runoff amount. SSF is the principal mechanism of runoff formation. It originates from matrix flow and pipe flow at the soil-bedrock interface, principally during the wet season. Matrix flow is correlated with soil moisture (SM) content, with a threshold of 25 %. Pipe flow starts with saturation of soil bottom but without saturation of the entire soil profile, due to a large network of macropores. Stream flow response is highly correlated with matrix flow behaviour in timing and intensity. SWR induces a very patchy moistening of the soil, concentrates the fluxes and accelerates them almost 100 times greater than normal percolation of the water in the matrix.

Keywords: Overland flow; Subsurface flow; Streamflow; Soil moisture; Eucalypt.

INTRODUCTION

In the Baixo Vouga region of north-central Portugal, forests now occupy almost half of the territory. Two thirds of these forests are plantations of Eucalyptus, that present a large economic interest as the principal raw material for paper pulp production.

The hydrological implications of this large-scale introduction of eucalypt monocultures plantation are currently being studied in a series of experimental headwater catchments, in the mountainous part of the Baixo Vouga region. The existing studies, however, have focused on overland flow (OLF) generation and, to a lesser extent, runoff generation at the catchment scale but the linkage between both scales has received little research attention so far. Furthermore, measurement of subsurface flow (SSF) has never been undertaken.

OLF is widely considered as an important hydrological pathway. While infiltration-excess OLF is generally associated with (semi-)arid climates (Albergel et al., 2003) and soils with much lower infiltration capacities than the forest soils in the study region, its potential importance in the streamflow response of the Caramulo headwater catchments cannot be discarded for various reasons. First, many Eucalyptus plantations in the study region are intensively managed with frequent use of machinery, and compaction of the soil surface is known to enhance the infiltration-excess OLF (Ziegler et al., 2001). Second, many Eucalyptus plantations in the Caramulo Mountains have a low ground cover of vegetation and litter and a high cover of stones, especially when they are recently planted, and infiltration-excess OLF is often associated with areas having sparse vegetation and/or a very stony soil surface (Ruiz-Sinoga et al., 2010). Third, the Eucalypt plantations in the study region are well-known for their strong to extreme soil water repellency, especially after dry spells (Doerr et al., 2000; Keizer et al., 2005a; Santos et al., 2013), and soil water repellency is widely regarded to induce infiltration-excess OLF (Ferreira et al., 2000; Keizer et al., 2005b; Leighton-Boyce et al., 2005; Malvar et al., 2013).

Also saturation-excess OLF can be expected to play an important role in streamflow generation in the study region, especially during the wet winter seasons when soil water repellency tends to be less pronounced (Doerr et al., 2000; Keizer et al., 2005a). Namely, rainfall is rather high in the upper Caramulo Mountains in particular, amounting to over 1400 mm per year, and soils tend to be shallow (Malvar et al., 2013; Shakesby et al., 1996). Bonell and Gilmour (1978), for example, found widespread saturation-excess OLF generation when high intensity rainfall combined with a perched water table.

SSF can equally be expected to contribute markedly to stream flow generation in the study region, due to the elevated rainfall and the steep slopes in the experimental headwater catchments. Two types of SSF are usually identified, i.e. lateral matrix flow and preferential flow in macropores and/or pipes.

Lateral matrix flow occurs in general on steep slopes with soils that have a high infiltration capacity and, at the same time, are shallow or have an impermeable or poorly permeable soil layer at limited depth. The behaviour of lateral matrix flow has been found to depend on soil depth (Hopp and McDonnell, 2009), soil porosity (Weiler and McDonnell, 2004), bedrock micro-topography (Tromp-van Meerveld and McDonnell, 2005).

Preferential flow though macropores could be important in the study region, as Eucalyptus trees develop extensive root networks during successive rotation cycles, re-sprouting vigorously after logging. Furthermore, preferential flow could be an important mechanism of infiltration under repellent soil conditions (Kramers et al., 2005; Santos et al., 2013).

The main aim of this exploratory study was to describe runoff generation at various spatial scales, in a catchment dominated by Eucalyptus plantations, in particular OLF, SSF processes and stream flow response. More specifically, to identify if these processes vary during the hydrological year and what is the influence of antecedent soil moisture (SM) conditions.

MATERIALS AND METHODS

Study area

The study was carried out in the foothills of the Caramulo Mountains of north-central Portugal (Figure 1). The area is mainly covered by forests and, in particular, Eucalyptus plantations, which now constitute a mosaic of stands in different rotation cycles. The prevalent Eucalypt species is *Eucalyptus globulus* Labill., which is a fast growing tree species that re-sprouts vigorously from multiple stems after logging. In the region, an Eucalyptus plantation typically involves three rotation cycles of 12–15 years each, after which a new plantation is established, in general following the removal of the existing root systems with deep ground operations such as rip-ploughing and bench terracing.

The climate of the study area is temperate with wet winters and dry summers, and can be classified as Csb according to the Köppen's system (DRA-Centro, 1998). The mean annual temperature varies between 12.5 and 15.0ºC, while mean annual precipitation varies between 1400 and 1600 mm (Atlas do Ambiente, 2001).

The Caramulo Mountains are part of the Hesperian Massif, which is dominated by Pre-Ordovician metamorphic sediments of the schist and greywackes complex. Slopes are typically very steep (>20 degrees), and soils are stony, weakly-structured and shallow. The soils of the study area are mapped – at a scale of 1:1,000,000 – as a complex of Humic Cambisols and, to a lesser extent, Dystric Litosols (Cardoso et al., 1971, 1973).

Study site and experimental design

The study was carried out in the Serra de Cima headwater sub-catchment of the Alfusqueiro River Basin. The sub-catchment was instrumented with a hydrometric station, three runoff plots and 3 trenches for measuring subsurface flow, a rainfall gauge and 8 SM sensors (Figure 1).

Rainfall was measured using a tipping-bucket rainfall gauge with a 0.2 mm resolution (Pronamic RAIN-O-MATIC Professional).

This Serra de Cima experimental sub-catchment (52 ha) is located between 273 and 485 m a.s.l., has steep slopes of, on average, 16º, and is covered for some 70% by mono-specific plantations of *Eucalyptus globulus* Labill. and for the remaining 30% by a mixed stand of eucalypt, maritime pine and acacias. The hydrometric station consisted of a H-flume, where the water level was recorded at 2-minute intervals using a pressure sensor (Campbell Scientific CS450).

The three runoff plots and the subsurface plot were installed in a hillslope with eucalypts in the second rotation cycle, which had been logged for the first time in 2002. In 2012, the density of Eucalyptus amounted to 970 trees.ha^{-1} and 1857 trunks.ha^{-1}, its total basal area and height were 16 m^2.ha^{-1} and ~12 m, respectively. The stand's understory was then dominated by broom (*Pterospartum tridentatum*), heather (*Erica spp.*) and gorse (*Ulex spp.* and *Genista spp.*), providing an almost complete soil cover and reaching heights of 80–100 cm. The stand's litter layer covered the soil almost completely and was typically some 10 cm thick, comprising an F-horizon of Eucalyptus bark, branches and decomposing leaves as well as an O-horizon. The plantation was located on a convex-linear hillslope, with a slope angle that ranged from 3º at the top till 27º at the bottom. The soils of the plantation varied between Humic Regosols on the convergent slope parts and Humic Leptosols on the remaining parts, with soil depths ranging from 20 to 80 cm. The soils are

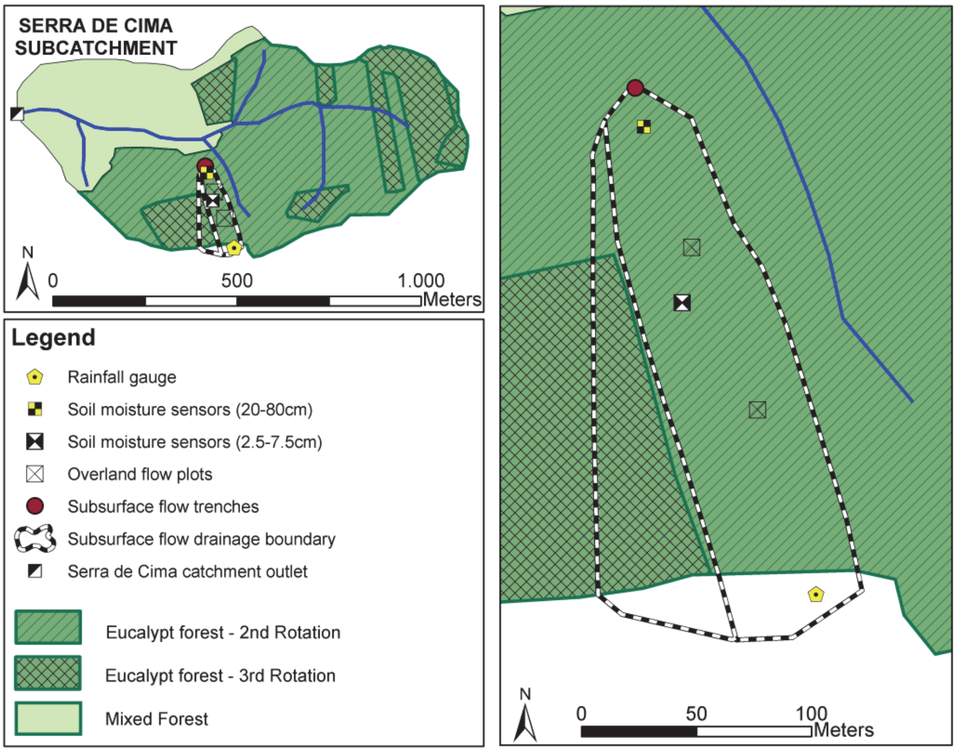

Fig. 1. Location of study area and study site in the Alfusqueiro River Basin, north-central Portugal, as well as land cover and experimental set-up in Serra de Cima headwater catchment.

very stony with stone fractions of roughly 50% in the topsoil, probably reflecting past ground operations. Soil texture is silt loam, with the silt fraction amounting to roughly 60% and the sand and clay fractions both to 20%. The topsoil is rich in organic matter, typically exceeding 10%.

The three runoff plots were located in the upper, middle and lower part of the study slope to assess OLF generation across the slope. The plots were 2 m wide by 8 m long (16 m^2), and were bounded by a flexible brass strip. The outlet of the runoff plots consisted of a wash trap (with a filter to retain coarse elements) that was connected to a tipping-bucket device.

The SSF was measured at the bottom of the hillslope, about 80 m upslope of the stream channel by three trenches excavated down to the bedrock. Each trench was 3 meters wide, and estimated to drain a convergent slope area of 1.9 ha. The water produced by each trench was first routed to a storage tank and then, using garden hose, to a tipping-bucket gauge equipped with an ONSET event data logger. SSF was estimated by subtracting the precipitation recorded by the automatic rain gauge. Field observations revealed that the central trench included seven macro-pores with a diameter of 3–8 cm that were situated just above the soil-bedrock interface as well as several smaller macro-pores situated some 40 cm above this interface. Other two trenches did not reveal any macro-pores. Hence, the central trench was inferred to produce SSF principally by pipe flow and the two other trenches exclusively by matrix flow. Accordingly, the central trench will be referred to underneath as "*SSF Pipe*" and the lateral trenches as "*SSF Matrix 1*" and "*SFF Matrix 2*".

Two sets of four SM sensors (Decagon EC-5) were installed with readings recorded at 15 min intervals. In the middle part of the slope (next to the middle runoff plot), two pairs of sensors were installed at five meter distance from each other (*a* and *b*) and at 2.5 cm and at 7.5 cm soil depth (SM 2.5 cm and SM 7.5 cm). The second set was installed in the bottom part of slope (next to the subsurface trenches) inserted vertically throughout the soil profile at 20, 40, 60 and, 80 cm soil depth (SM 20 cm, SM 40 cm, SM 60 cm and SM 80 cm).

Data collection and analysis

The data used in this study were analysed at a temporal resolution of one hour. While rainfall, OLF and stream flow were analysed in mm h^{-1}, SSF was expressed in $L.h^{-1}$. This was done because no information was available on bedrock topography and, the Digital Terrain Model (DTM) only provided an unreliable estimate of the subsurface drainage area (Freer et al., 2002). SSF was analysed separately for the three individual trenches. The data were collected during the 2013/14 hydrological year, starting on 1 of October 2013 and ending on 30 of September 2014. During this period, a total of five rainfall-runoff events were selected to demonstrate differences in soil wetting and runoff response under dry, intermediate and wet antecedent SM conditions. In order to separate the events in those 3 classes, the average of SM content through the soil profile was calculated (SM surface (2.5 and 7.5 cm), SM 20 cm, SM 40 cm, SM 60 cm and SM 80 cm). The SM content thresholds of 15% and 25% of were considered to distinguish the events under dry, intermediate and wet antecedent conditions.

RESULTS

An overview of the analysed events is given in Table 1 and a detailed description of their main features is presented in the next sections. The reason for including three subsequent dry events rather than a single one of them was that their sequence illustrated well the wetting-up of the soil after a dry spell, with antecedent topsoil moisture contents increasing gradually from the first till the third event. In fact, the antecedent topsoil moisture contents of the third dry event differed little from those of the intermediate event (SM at topsoil min-max 19–28 vs. 20–29%, respectively) but the moisture contents at greater soil depth did show a marked contrast between the dry and intermediate events (6–17 vs. 10–24%) This initial wetting-up process occurred relatively late in the year, as November 2013 registered

Table 1. Summary of the main characteristics of five selected rainfall-runoff events according to antecedent soil moisture conditions (dry-intermediate-wet) in a mono-specific eucalypt plantation, plot and slope scale and a eucalypt-dominated catchment. Acronyms are: OLF, overland flow; Q, streamflow; SSF, subsurface flow.

		EVENTS				
			Dry		Intermediate	Wet
Date		13-12-2013	17-12-2013	19-12-2013	24-12-2013	09-02-2014
Event conditions						
Total rainfall amount (mm)		18	14	60	95	34
Maximum hourly rainfall ($mm.h^{-1}$)		4	5	12	16	6
SM antecedent-top soil (< 10 cm deep); (%); min/average/max		6/9/13	13/17/20	19/23/28	20/26/29	23/34/45
SM antecedent (20–80 cm deep); (%); min/average/max		6/11/14	6/12/14	6/13/17	10/17/24	12/24/33
Event response	Drainage area					
OLF peak ($mm.h^{-1}$)	16 m^2	0.015	0.008	0.060	15.000	0.008
OLF coefficient (% rainfall)		0.15	0.18	0.46	28.70	0.12
SSF total amount (l)	1.92 ha	0	0	6094	22063	> 5962
SSF peak ($l.h^{-1}$)		0	0	860	1076	> 780
SSF per unit of rainfall ($l.mm^{-1}$ rainfall)		0	0	102	232	> 216
Q peak ($mm.h^{-1}$)	52 ha	base	base	0.7	6.0	1.2
Q coefficient (% rainfall)		0	0	18.2	55.9	23.1

lower precipitation than the 10-years average (70 mm vs. 172 mm, Fig. 2). Equally, the analysed wet event occurred under exceptional wetter conditions, as precipitation in January and February 2014 was much higher than the average for these months (442 mm vs. 174 mm, and 360 mm vs. 119 mm, respectively, Fig. 2).

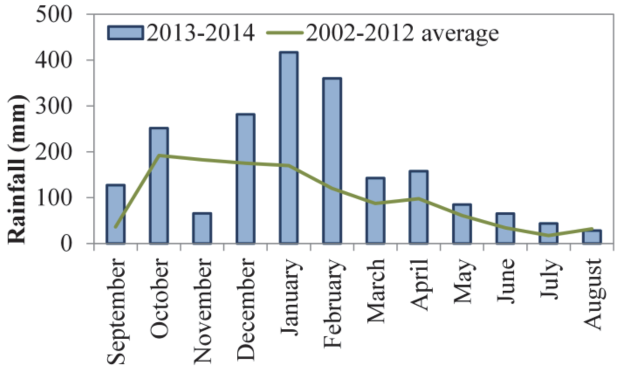

Fig. 2. Monthly precipitation for the hydrological year 2013–2014 compared with 10-years (2002–2012) average monthly rainfall.

Three successive rainfall-runoff events under dry antecedent soil moisture conditions

The third dry rainfall event registered the higher rainfall amount, intensity and SM content when compared with the two previous events. Consequently, only this third event produced some relevant OLF, SSF and streamflow (Fig. 3). Nevertheless, the OLF production was as low as 0.06 mm.h^{-1} or less than 0.5% of rainfall (Table 1).

The topsoil wetting pattern was similar for the three dry events, but it was not spatially homogenous as one measurement point remains dry while the others suffer a progressive moistening (Fig. 3b). This pattern differs from the classic progression of a wetting front.

The SSF was solely the result of matrix flow (Fig. 3d). It initiated when the SM content at 20 and 40 cm depth had reached a threshold of 25%. The stream flow hydrograph matched closely the rising limb of the matrix SSF hydrograph, registering a peak of 0.7 mm.h^{-1} and a coefficient of about 18% (Fig. 3e).

A rainfall-runoff event with intermediate antecedent soil moisture conditions

The intermediate rainfall event involved the largest rainfall amount (95 mm) and the highest hourly rainfall intensity (16 mm.h^{-1}) than any of the other analysed events, registering also the largest OLF, SSF and stream responses (Table 1).

The topsoil wetting pattern is similar to the third dry event. However, only before the rainfall intensity peak of the intermediate event, the SM at the deeper soil layer behaved in a similar manner than during the third dry event. During the second part of the event, when the SM content at 40 cm depth attained a threshold of 35% (simultaneously with rainfall intensity peak) the SM content at 80 cm started an extremely fast moistening until it achieved saturation (SM > 50%) in less than 15 minutes. After saturation of the SM 80 cm, only half an hour is necessary to saturate SM 60cm. The drainage of SM 60cm was extremely fast compared to others other soil layers (Fig. 4c).

The OLF generation clearly exceeded that of any other dry or wet event, amounting to 29% of the rainfall (Table 1). One quarter of OLF production occurred during the rainfall intensity peak and the remaining amount remarkably during a spell without rainfall following the intensity peak (Fig. 4a).

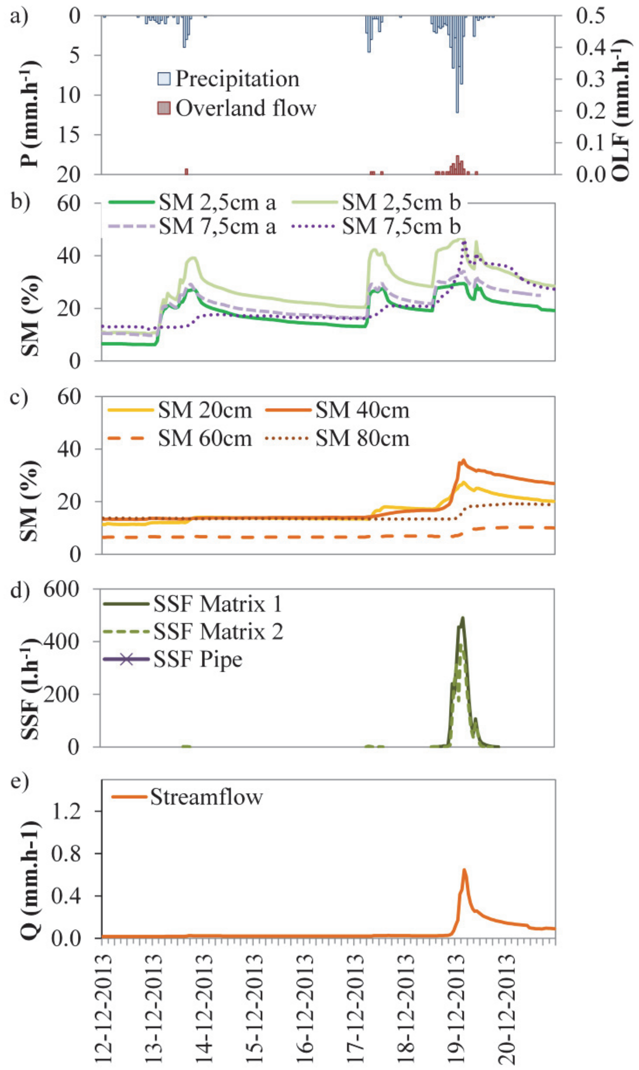

Fig. 3. Precipitation (P) and overland flow (OLF) (a), soil moisture (SM) content at different soil depths (b, c), subsurface flow (SSF) (d) and stream flow (Q) (e) for three selected events with "dry" antecedent soil moisture conditions in a mono-specific eucalypt plantation and a eucalypt-dominated catchment.

The SSF response of intermediate event agreed with that of third dry event in various aspects: (i) significant matrix flow preceded significant pipe flow; (ii) matrix flow started before SM at 20 and 40 cm depth reached its maximum (iii) the matrix peak flows differed roughly about 100 L.h^{-1} in both events.

A substantial amount of pipe SSF is produced (200 L.h^{-1}) before SM contents at 60 and 80 cm even started to increase markedly but did not produce peak values till SM contents at these depths reached their maximum values. Pipe subsurface peak flow continued to occur for more than 24 hours (Fig. 4d). By contrast, matrix SSF was closely associated to SM contents at 40 cm depth (Fig. 5).

The stream flow response was the most pronounced of all the analysed events with a peak of 6 mm.h^{-1} and a coefficient of 55.9%. Similarly to the third dry event, the rising limps of the

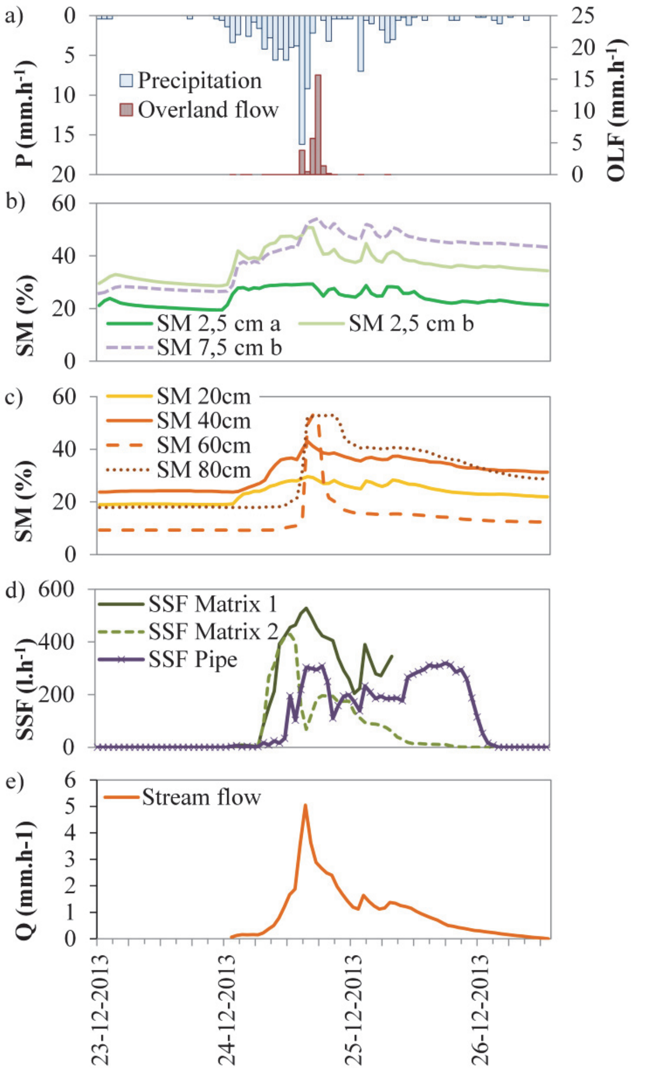

Fig. 4. Precipitation (P) and overland flow (OLF) (a), soil moisture (SM) content at different soil depths (b, c), subsurface flow (SSF) (d) and stream flow (Q) (e) for a selected event with "intermediate" antecedent soil moisture conditions in a mono-specific eucalypt plantation and a eucalypt-dominated catchment.

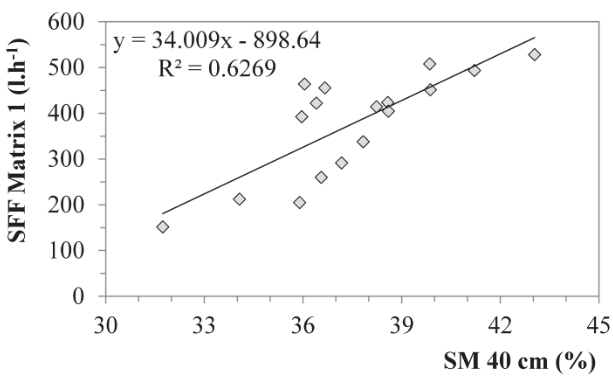

Fig. 5. Relationship of subsurface flow from the SFF Matrix 1 with soil moisture content at 40 cm depth for the rainfall-runoff event with "intermediate" antecedent soil moisture conditions.

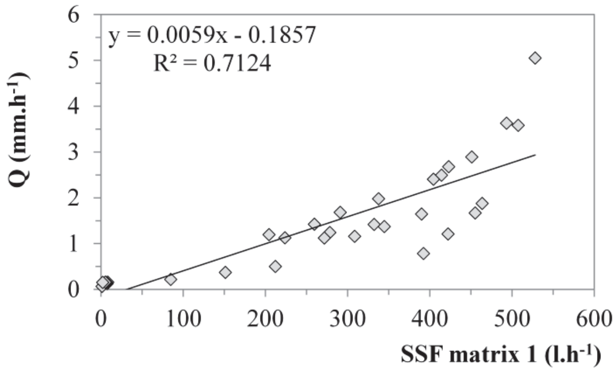

Fig. 6. Relationship of stream flow with subsurface flow from the SFF Matrix 1 for the rainfall-runoff event with "intermediate" antecedent soil moisture conditions.

stream and the matrix SSF hydrographs presented a good agreement (Fig. 6). However, the stream flow peak clearly preceded the OLF peak as much as 2 hours (Fig. 4a and Fig. 4e).

A rainfall-runoff event with wet antecedent soil moisture conditions

The wet event was a relatively minor amount (34 mm) and low-intensity (6 $mm.h^{-1}$) storm, although, it occurred after an exceptionally rainy January (416 mm). Consequently, SM contents were at the maximum values recorded during this study (Table 1). On the other hand, the OLF, SSF and stream flow response were comparable to that of the dry events.

Unlike any of the other four events, it produced no major variations in topsoil moisture contents (Fig. 7b). Equally, the SM content in the soil profile revealed a slight response to the rainfall input. Still, there was a marked contrast, between the SM contents at 20, 40 and 80 cm depth and those at 60 cm depth. While the former closely corresponded to the maximum values recorded in the various events, the latter did not, remaining below the peak figures of over a 50 % of the attained during the intermediate event.

Contrary to the other events, a significant increase on pipe SSF happened prior to the matrix SSF, and the peak of matrix SSF correspond exactly to a deep decrease of pipe SSF discharge. Afterwards, as matrix SSF discharge declined, pipe SSF discharge increases again (Fig. 7d). The pipe SSF peak was basically the same for both intermediate and wet events (c. 300 $L.h^{-1}$), while the matrix SFF peak was roughly twice in the intermediate than in the wet event (500 vs. 250 $L.h^{-1}$). Opposite to the intermediate event, the pipe SSF peak happened without saturation of the deeper soil layers.

The stream flow increase was similar to that in the third dry event, about 0.6 $mm.h^{-1}$, with a peak flow of 1.2 $mm.h^{-1}$. The base flow, though, at the start of the wet event was clearly higher, confirming the overall wetness of the study catchment. In terms of stream flow coefficient the overall value was about 23%, comparable to the dry event but twice lower than for the intermediate event (Table 1). Similarly to what was observed earlier, the rising limbs of the stream flow and the matrix SSF hydrographs agreed remarkably well (Fig. 7d and Fig. 7e).

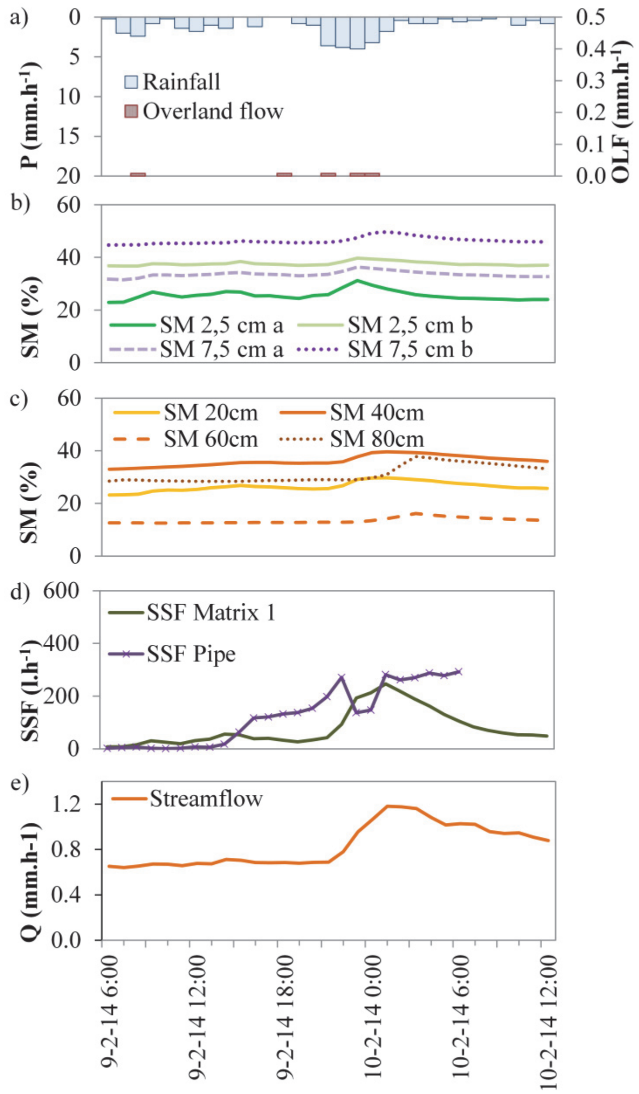

Fig. 7. Precipitation (P) and overland flow (OLF) (a), soil moisture (SM) content at different soil depths (b, c), subsurface flow (SSF) (d) and stream flow (Q) (e) for a selected event with "wet" antecedent soil moisture conditions in a mono-specific eucalypt plantation and a eucalypt-dominated catchment.

DISCUSSION
Overland flow

Eucalypt plantations are widely held to involve not only saturation-excess but also infiltration-excess OLF, mainly due to the association of eucalypts with strong to extreme soil water repellency. In the study area, following dry spells and with presence of strong soil water repellency, rainfall events produced negligible amounts of OLF as well-illustrated by the dry events. It is well-established that soil water repellency and its high spatial variability (Keizer et al., 2005a; Leighton-Boyce, 2003; Santos et al., 2013) promote spatially localized infiltration or percolation, with the development of fingered or preferential flow paths, which can explained the observed low production of OLF. Nevertheless, during the dry period, SSF came exclusively from the soil matrix, therefore, the water that infiltrated by preferential paths was reabsorbed by soil matrix.

The elevated spatial variability in key soil properties might produce a combination of infiltration-excess and saturation-excess OLF. The intermediate event illustrated well the OLF generation by both processes. During the intermediate event, a 15-minute peak in rainfall intensity of 34 mm.h^{-1} produced an instantaneous runoff coefficient of 47% at one of the OLF plots, while topsoil moisture contents were still below their maximum values. However, Boulet et al. (2007) estimated infiltration capacity in nearby soils to be about 30 mm.h^{-1}, so that the high runoff coefficient can be partially originated by saturation-excess OLF. This spatial heterogeneity is well-demonstrated by the fact that the other two runoff plots produced any OLF during this peak rainfall intensity. Furthermore, two types of saturation excess OLF seemed to be involved, i.e. saturation resulting from infiltration of rainfall and return flow. The clear peak in OLF that occurred after the rainfall had stopped (Fig. 4a), suggested that the second mechanism was the principal source of the measured runoff. The return flow mechanism could be enhanced by the highly irregular topography of the bedrock that was observed in the subsurface trenches. Abrupt differences in soil depth could lead to exfiltration of subsurface flow. Sidle et al. (2000) demonstrated that return flow was controlled by soil depth as well as hillslope position within the catchment. In the present case, the importance of hillslope position in return flow was suggested by the fact that only the lowermost of the three runoff plots revealed a post-rainfall peak in OLF.

Subsurface and streamflow

The measurement of SSF provided valuable first insights into the hydrology of the study site as well as the experimental catchment, but it proved to be a challenge, also because flow volumes were much higher than expected. A key issue was the complexity of the SSF response, with marked variations between the selected rainfall-runoff events and, within the events, in time and space. SSF was originated both by matrix flow and pipe flow at the soil-bedrock interface. During the dry season SSF was produced exclusively for matrix flow and during the intermediate and wet season for pipe and matrix flow.

Matrix flow was correlated with SM content at 40 cm soil depth and not with a rainfall amount threshold as demonstrated by Tromp-van Meerveld and McDonnell (2006). A threshold of 25% of SM at 40 cm was necessary for matrix flow initiation. Furthermore, the matrix SSF intensity was also varying as a function of SM content, especially with soil moistening at 40 cm depth, in such a way that the matrix SSF switched off when SM content attained a steady state.

The matrix SSF discharge is also closely correlated with the streamflow discharge, both in terms of timing and intensity.

Pipe flow behaviour was related with bottom moisture content, but not directly correlated with it. During the intermediate event, the initiation of pipe SSF is delayed relatively to the matrix subsurface flow. It required soil bottom saturation - occurring extremely fast - but without complete saturation of the soil profile, by dint of a large network of macropores. Observations in the field showed that pipe SSF is initially produced by large pipes situated at soil-bedrock interface, and enhanced later by the activation of smaller pipes situated higher in the soil profile, confirming the rise of the water table. The maximum pipe flow rate was sensitive to the measured rainfall intensity, as also determined by Uchida et al. (2005). The pipe SSF remained active during 24 h after the rainfall event peak, and was very sensitive to new small rainfall inputs (with a lag time of about one hour). During the wet event, SM content is near the steady state, so a moderate input of rainfall leads to the re-ignition of the pipe SSF without requiring saturation of the soil bottom, as the pipe network stayed connected for such SM conditions.

Soil wetting

During dry events, with strong to severe soil water repellency presence, the infiltration was restricted to a network of preferential paths, nonetheless not well connected, and leading to the reabsorption of the water by the soil matrix. With the progressive soil matrix moistening, the repellency severity at soil surface was mitigated and the soil wetting pattern became more homogeneous at soil surface. A threshold between 19% and 23% of SM content was indicated by Santos et al. (2013) and Leighton Boyce et al. (2005), for the soil become wettable. The present study data did not allow determining a threshold of SM for wettable soil conditions, but it indicated a clear delay in moistening for one SM sensor in 7.5 cm soil depth. On the deeper soil layers, as the SM content at 20 cm depth attained a threshold of 22%, the soil matrix stopped to reabsorb the water travelling through the preferential paths, allowing a connection of the network, which leads to the moistening of the soil at 40, 60 and 80 cm depth, especially fast at 40 cm depth. In fact, the presence of preferential flow paths concentrated the water movement in restricted areas, enhancing the velocity of water travelling through the soil. For example, during the intermediate event, as SM at 40 cm attained a threshold of 35%, the SM at 80 cm depth achieved saturation in less than 15 minutes, which corresponds to a water circulation about 100 times higher than normal percolation velocity of water in the matrix, determinate for the study area by Boulet et al. (2007). Mosley (1979) also observed a water movement in the soil 300 times greater than the measured soil hydraulic conductivity.

Globally, it was observed in the study area that after the topsoil had reached field capacity the circulation of water through the soil profile became extremely fast. It was possible through the free water circulation in the macropores network that canalized directly the water to the soil bottom, leading to the saturation of the deeper layer and the subsequent quick rise of the water table. During the wet season, field observations of the trenches revealed the presence of large areas completely dry and severely water repellent. Gosch (2012), in the same study area, with the use of brilliant blue experiments demonstrated that soil moistening through the soil profile was highly spatially heterogeneous, presenting patches of almost dry and close to saturation areas. Sanda and Cislerova (2009) also observed that fast infiltration of the water by preferential flow paths allowed the saturation of the soil above the soil-bedrock interface which leaded to the rapid formation of SSF. These founding are also compatible with the model proposed by McDonnell (1990), where rainfall infiltrated quickly to depth via vertical cracks, as rainfall intensity exceed soil surface matrix hydraulic conductivity then the water perches at the soil bedrock interface, and "back up" to the newly saturated matrix. Once free water exists, larges pipes in the lower soil zone quickly dissipate transient water tables laterally.

CONCLUSIONS

The main conclusions of this research regarding the water fluxes processes in a eucalypt plantation hillslope and a eucalypt-dominated catchment were the following. OLF generation was highly spatially heterogeneous, as two of three plots had produced negligible runoff amounts. OLF generation was produced by a combination of infiltration-excess and saturation-excess processes. During the dry season, infiltration-excess was the main mechanism, due to the presence of strong soil water repellency. However, total runoff amount is very low. During the wet season, OLF was mainly originated by saturation excess, and particularly as return flow. However, infiltration-excess OLF also occurred exceptionally under very high rainfall intensity peaks.

SSF was originated both by matrix and pipe flow at the soil-bedrock interface. During the dry season SSF was produced exclusively as matrix flow and during the intermediate and wet season as matrix and pipe flow.

Matrix flow discharge was closely correlated with SM content. Matrix flow initiation occurred with a 25% of SM content threshold at 40 cm soil depth but was not possible to define a rainfall amount threshold.

Pipe flow discharge is influenced by the rainfall intensity, it persisted longer than matrix flow until all free water is drained. Pipe flow initiation differed for intermediate and wet antecedent SM contents. In the former, it was delayed relatively to the matrix flow, starting after the saturation of soil bottom but without saturation of top soil. In the latter case, pipe flow initiation was instantaneous, prior the matrix flow, and without saturation of soil bottom.

Stream flow response was highly correlated with matrix flow behaviour in timing and intensity, indicating that SSF was the most important process for the hydrological response of the studied catchment.

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REFERENCES

Albergel, J., Moussa, R., Chahinian, N., 2003. Les processus hortoniens et leur importance dans la genèse et le développement des crues en zones semi-arides. [Hortonien processes and their importance in the genesis and development of floods in semi-arid areas]. La Houille Blanche, 6, 65–73. (In French.)

Atlas do Ambiente, 2001. Agência Portuguesa do Ambiente, Ministério da Agricultura, do Mar, do Ambiente e do Ordenamento do Território. http://sniamb.apambiente.pt/webatlas/

Bonell, M., Gilmour, D.A., 1978. The development of overland flow in a tropical rainforest catchment. Journal of Hydrology, 39, 3–4, 365–382.

Boulet, A.-K., Prats, S.A., Ferreira, A.J.D., Coelho, C.O.A., 2007. Estudo dos padrões espaciais e temporais dos processos de infiltração e de evapotranspiração à escala da vertente para vários tipos de maneio de eucaliptais. [Spatial and temporal patterns of infiltration and evapotranspiration processes at slope scale for various eucalyptus stands managements]. In: Proc. 9th Environmental National Conference, Apr 18-2007, Aveiro, Portugal, 1, pp. 214–221. (In Portuguese.)

Cardoso, J.C., Bessa, M.T., Marado, M.B., 1971. Carta dos solos de Portugal (1:1,000,000). [Soils map of Portugal (1:1,000,000)]. Serviço de Reconhecimento e de Ordenamento Agrário, Secretaria de Estado da Agricultura, Lisbon, Portugal. (In Portuguese.)

Cardoso, J.C., Bessa, M.T., Marado, M.B., 1973. Carta dos solos de Portugal (1:1,000,000). [Soils map of Portugal (1:1,000,000)]. Agronomia Lusitana, 33, 461–602. (In Portuguese.)

Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., 2000. Soil water repellency: its causes, characteristics and hydrogeomorphological significance. Earth-Science Reviews, 51, 33–65.

DRA-Centro (Direcção Regional do Ambiente do Centro) 1998. Plano de bacia hidrográfica do Rio Vouga, 1a fase, Análise e diagnóstico da situação de referência, Análise biofísica, Anexos. [Watershed plan of Vouga River, first phase, analysis and diagnosis of the baseline, biophysical analysis, Annex]. Lisbon, Portugal. (In Portuguese.)

Ferreira, A.J.D., Coelho, C.O.A., Walsh, R.P.D., Shakesby, R.A., Ceballos, A., Doerr, S.H., 2000. Hydrological implications of soil water repellency in Eucalyptus globules forests, north-central Portugal. Journal of Hydrology, 231–232, 165–177.

Freer, J., McDonnell, J.J., Beven, K.J., Peters, N.E., Burns, D.A., Hooper, R.P., Aulenbach, B., Kendall, C., 2002. The role of bedrock topography on subsurface storm flow. Water Resources Research, 38, doi: 10.1029/2001WR000872

Gosch, L., 2012. Einfluss unterschiedlicher Forstmanagementstrategien auf bodenhydraulische Parameter zur Standortswassermodellierung im Águeda Einzugsgebiet Zentralportugal. [Effects of different forest management strategies on soil hydraulic parameters for on site water modeling in Agueda basin, Central Portugal]. Diplomarbeit, Technische Universität Dresden. Thesis, Technical University of Dresden. (In German.)

Hopp, L., McDonnell, J.J., 2009. Connectivity at the hillslope scale: Identifying interactions between storm size, bedrock permeability, slope angle and soil depth. Journal of Hydrology, 376, 378–391.

Keizer, J.J., Coelho, C.O.A., Matias, M.J.S., Domingues, C.S.P., Ferreira, A.J.D., 2005a. Soil water repellency under dry and wet antecedent weather conditions for selected land-cover types in the coastal zone of central Portugal. Australian Journal of Soil Research, 43, 3, 297–308.

Keizer, J.J., Coelho, C.O.A., Shakesby, R.A., Domingues C.S.P., Malvar, M.C., Perez, I.M.B., Matias, M.J.S., Ferreira, A.J.D, 2005b. The role of soil water repellency in overland flow generation in pine and eucalypt forest stands in coastal Portugal. Australian Journal of Soil Research, 43, 3, 337–350.

Kramers, G., van Dam, J.C., Ritsema, C.J., Stagninin, F., Oostindie, K., Dekker, L.W., 2005. A new modelling approach to simulate preferential flow and transport in water repellent porous media: parameter sensitivity, and effects on crop growth and solute leaching. Australian Journal of Soil Research, 43, 3, 371–382.

Leighton-Boyce, G., Doerr, S.H., Walsh, R.P.D., Shakesby, R.A., Ferreira, A.J.D., Boulet, A-K., Coelho, C.O.A., 2003. Spatio-temporal patterns of soil water repellency in Portuguese eucalyptus forests and implications for slope hydrology. In: Servant, E., Najem, W., Leduc, C., Shakeel, A. (Eds.): Hydrology of Mediterranean and Semiarid Regions. IAHS Publication, 278, pp. 111–116.

Leighton-Boyce, G., Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., Ferreira, A.J.D., Boulet, A.-K., Coelho, C.O.A., 2005. Temporal dynamics of water repellency and soil moisture in eucalypt plantations, Portugal. Australian Journal of Soil Research, 43, 3, 269–280.

Malvar, M.C., Martins, M.A., Nunes, J.P., Robichaud, P.R., Keizer, J.J., 2013. Assessing the role of pre-fire ground preparation operations and soil water repellency in post-fire runoff and inter-rill erosion by repeated rainfall simulation experiments in Portuguese eucalypt plantations. Catena, 108, 69–83.

McDonnell, J.J., 1990. A rationale for old water discharge through macropores in a steep, humid catchment. Water Resources Research, 26, 11, 2821–2832.

Mosley, M.P., 1979. Streamflow generation in a forested watershed, New Zealand. Water Resources Research, 15, 795–806.

Ruiz Sinoga, J.D., Romero Díaz, A., Ferre Bueno, E., Martínez Murillo, J.F., 2010. The role of soil surface conditions in regulating runoff and erosion processes on a metamorphic hillslope (Southern Spain): Soil surface conditions, runoff and erosion in Southern Spain. Catena, 80, 131–139.

Sanda, M., Cislerova, M., 2009. Transforming hydrographs in the hillslope subsurface. Journal of Hydrology and Hydromechanics, 57, 4, 264–275.

Santos, J.M., Verheijen, F.G.A., Wahren F.T., Wahren A., Gosch, L., Bernard-Jannin L., Rial-Rivas, M.E., Keizer, J.J., Nunes, J.P., 2013. Soil water repellency dynamics under pine and eucalypt – a high-resolution time series. Land Degradation & Development, doi: 10.1002/ldr.2251

Shakesby, R.A., Boakes, D.J., Coelho, C.D.A., Gonçalves, A.J.B., Walsh, R.P.D., 1996. Limiting the soil degradation impacts of wildfire in pine and eucalyptus forests, Portugal: comparison of alternative post-fire management practices. Applied Geography, 16, 4, 337–355.

Sidle, R.C., Tsuboyama, Y., Noguchi, S., Hosoda, I., Fujieda, M., Shimizu, T., 2000. Stormflow generation in steep forested headwaters: a linked hydrogeomorphic paradigm. Hydrological Processes, 14, 369–385.

Tromp-van Meerveld, H.J., McDonnell, J.J., 2005. Comment to "Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes, Journal of Hydrology 286: 113-134". Journal of Hydrology, 303, 307–312.

Tromp-van Meerveld, H.J., McDonnell, J.J., 2006. Threshold relations in subsurface stormflow: 1. A 147-storm analysis of the Panola hillslope. Water Resources Research, 42, doi: 10.1029/2004WR003778

Uchida, T., Tromp-van Meerveld, I., McDonnell, J.J., 2005. The role of lateral pipe flow in hillslope runoff response: an intercomparison of non-linear hillslope response. Journal of Hydrology, 311, 1, 117–133.

Weiler, M., McDonnell, J.J., 2004. Virtual experiments: A new approach for improving process conceptualization in hillslope hydrology. Journal of Hydrology, 285, 3–18.

Ziegler, A.D., Giambelluca, T.W., Sutherland, R.A., Vana, T.T., Nullet, M.A., 2001. Contribution of Horton overland flow contribution to runoff on unpaved mountain roads in northern Thailand. Hydrological Processes, 15, 3203–3208.

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