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Title: Differences in overland flow, hydrophobicity and soil moisture dynamics between Mediterranean woodland types in a peri-urban catchment in Portugal

Article Type: Research Paper

Keywords: Eucalypt plantations; oak woodland; saturation-excess overland flow; infiltration-excess overland flow; hydrophobicity; soil moisture content.

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Abstract: Forest hydrology has been widely investigated, but the impacts of different woodland types on hydrological processes within a peri-urban catchment mosaic are poorly understood. This paper investigates overland flow generation processes in three different types of woodland in a small (6.2 km2) catchment in central Portugal that has undergone strong urban development over the past 50 years. A semi-natural oak stand and a sparse eucalyptus stand on partly abandoned peri-urban land and a dense eucalyptus plantation were each instrumented with three 16 m2 runoff plots and 15 throughfall gauges, which were monitored at c. 1- to 2-week intervals over two hydrological years. In addition, surface moisture content (0-5cm) and hydrophobicity (0-2cm, 2-5cm and 5-10cm) were measured at the same time as overland flow and throughfall. Although all three woodland types produced relatively little overland flow (< 3% of the incident rainfall overall), the dense eucalypt stand produced twice as much overland flow as the sparse eucalypt and oak woodland types. This contrast in overland flow can be attributed to infiltration-excess processes operating in storms following dry antecedent weather when severe hydrophobicity was widespread in the dense eucalypt plantation, whereas it was of moderate and low severity and less widespread in the sparse eucalypt and oak woodlands, respectively. In contrast, under wet conditions greater (albeit still small) percentages of overland flow were produced in oak woodland than in the two eucalypt plantations; this was probably linked to saturation-excess overland flow being generated more readily at the oak site as a result of its shallower soil. Differences in water retention in surface depressions affected overland flow generation and downslope flow transport. Implications of the seasonal differentials in overland flow generation between the three distinct woodland types for the hydrological response of peri-urban catchments are addressed.

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Dear Dr Konstantine Georgakakos, editor of the Journal of Hydrology,

I am enclosing herewith a manuscript entitled "Differences in overland flow, hydrophobicity and soil moisture dynamics between Mediterranean woodland types in a peri-urban catchment in Portugal" for evaluation and possible publication in Journal of Hydrology. The manuscript is a research paper prepared by Carla Ferreira, Richard Shakesby, Rory Walsh, Jacob Keizer, Daniel Soares, Óscar González-Pelayo, Celeste Coelho and António Ferreira. The submission includes the manuscript file which comprise 11322 words, as well as 6 figures and 2 tables.

The manuscript is a research article which investigate overland flow differences from three major woodland types, settled in a Portuguese peri-urban catchment. The study is based on runoff plot experiments and include soil hydrophobicity, soil moisture content and overland flow measurements over two years. Results show that dense eucalypt plantations generate significant higher overland flow than open eucalypt and oak stands. In dense eucalypt plantation, overland-flow is more prone under dry weather due to infiltration-excess mechanisms, enhanced by severe and widespread hydrophobicity. In sparse eucalypt stands overland flow is mostly linked to surface saturation, enhanced by a clayey soil with a comparatively high bulk density, whereas in oak woodland it is instead dependent on subsurface saturation, enhanced by shallower soil. Nevertheless, vertical water fluxes are dominant, favoured either by preferential flow pathways and/or high soil permeability, resulting from both the sandstone and limestone lithologies. The role of woodland types as potential sinks and/or sources of overland flow, particularly during extreme storm events, within peri-urban catchments is also discussed. We believe these findings and discussion will be of interest to the readers of your journal.

All the authors have directly participated in the planning, execution or analysis/discussion of the work, and have read and agree with the version of the manuscript submitted. The contents of this manuscript have not been copyrighted or published previously, and are not under consideration for publication elsewhere.

Any query should be addressed to the corresponding author, Carla Sofia Santos Ferreira - email: carla.ssf@gmail.com, cferreira@esac.pt, phone: 00351 932213748 (address is presented in the top of this letter).

The authors hope you find our manuscript suitable for publication and look forward to hearing from you.

Carla Sofia Santos Ferreira

Carla Sofia Santos Ferreira (PhD student)
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(Signature of corresponding author on behalf of all authors)
9th April 2015

Highlights

- Overland flow differences between dense eucalypt, sparse eucalypt and oak stands.
- Dense eucalypt plantation provides greater overland flow.
- Hydrophobicity enhances infiltration-excess overland flow in dense eucalypt stands.
- Long-lasting rainfall events favour overland flow in sparse eucalypt and oak stands.
- Woodland areas as sources and sinks of overland flow in peri-urban catchments.

Replies to the Editors and Reviewers

The authors were pleased to receive the decision of publication with minor revision in Journal of Hydrology, and would like to thank the referees and associated editor for the relevant contribution to improve the manuscript. The revised version of the manuscript has improved the quality of the English, in order to clarify some sentences, and addresses the points made by the associate editor and reviewer#2 as presented below. The number of lines where the changes are addressed on the new version of the manuscript regards to the marked manuscript file.

A) COMMENTS OF THE ASSOCIATE EDITOR

Comment: "1. I raised the issue about the difference between the earlier published paper "Spatiotemporal variability of hydrologic soil properties and the implications for overland flow and land management in a peri-urban Mediterranean catchment". The authors did attempt to explain the differences in their response.
First, I think that these differences should also be stated in the manuscript itself."

Response:
Following the suggestion, the authors added information regarding to earlier published paper "Spatiotemporal variability of hydrologic soil properties and the implications for overland flow and land management in a peri-urban Mediterranean catchment" on the Introduction section of the current manuscript, and state that current research was build-upon previous published work. Changes were performed as following:

> "Impacts of different forest and woodland stands on overland flow may be particularly important in the hydrology of small peri-urban catchments, as they are often characterized by a mosaic of different urban and non-urban land-uses, including woodland types on areas of altered or abandoned forest or agricultural management, as well as patches of pre-existing managed forest. Theoretically in such catchments, patches of forest types with permeable soil can break flow connectivity over the landscape and act as sinks to overland flow from upslope urban surfaces, whereas any overland flow generated on forest types with soils of lower permeability may reach downslope urban surfaces and represent an additional contribution to the urban flood hazard (Ferreira et al., 2015). Such peri-urban situations, particularly in areas of Mediterranean climate, have been little studied.
>
> This paper investigates the influence of three different types of woodland occurring within a peri-urban mosaic on overland flow generation in the *Ribeira dos Covões* catchment in an area of Mediterranean climate in central Portugal. Two of the woodland types investigated ((i) sparse eucalyptus adjacent to eucalyptus plantations and (ii) oak woodland) have been strongly influenced by semi-abandonment of land with peri-urbanization, whereas the third comprises pre-existing managed dense eucalyptus. A previous investigation in the same catchment (Ferreira et al. (2015) assessed temporal changes in soil properties (soil matrix infiltration capacity, soil moisture content and hydrophobicity at a network of points in different landscape

> units found in the catchment (woodland-sandstone, woodland-limestone, agriculture-sandstone, agriculture-limestone, urban-sandstone and urban-limestone); it then discussed their potential impacts on overland flow within the catchment. Results suggested that woodland areas might provide important sinks of overland flow during wet periods due to the high infiltration capacities recorded on their soils, but might act as overland flow sources in storms following dry periods (especially in summer) because of the hydrophobic nature of the soil matrix. The current paper tests these tentative suggestions of the previous paper by using a plot-scale monitoring approach to assess temporal differences in overland flow generation, and its influencing factors, between the sparse eucalyptus, oak woodland and managed dense eucalyptus woodland types over a two-year period. The focus is on the roles played by differing temporal regimes in hydrophobicity and soil moisture of the three woodland types studied. The implications of the results for planning land-use mosaics in peri-urban catchments in such environments are also explored." (lines 110-143)

Comment: "Second, some of the conclusions at least appear to be resembling each other. For example, the authors attempted to explain the higher overland flow volume from dense eucalypt on the basis of hydrophobicity of soil during dry conditions. Whereas, the earlier paper states in the abstract

"Infiltration-excess overland flow was generated in rainfalls during the dry summer season in woodland on both sandstone and limestone and on agricultural soils on limestone due probably in large part to soil hydrophobicity".

Despite differing instrumentation focus, the conclusions are clearly connected. Therefore, he lessons learned from the prior study should be summarized in this paper as well."

Response:
The authors agree that conclusions from earlier published paper should be summarized on current manuscript. The comparison of current manuscript results with previous published manuscript was performed within the Discussion section:

> "In storm events following dry weather, the most likely cause of overland flow seemed to be infiltration-excess caused by hydrophobic soils, as suggested by Ferreira et al. (2015)." (lines 512-513)
>
> "Overland flow responses, however, tend to diminish with increasing contributing area (van de Giesen et al., 2000, 2005; Ferreira et al., 2011; Chamizo et al., 2012). Based on measurements of soil hydrological properties at point-scale, Ferreira et al. (2015) suggested that woodland areas in *Ribeira dos Covões* could be an important source of overland flow in storm events during and immediately following the summer dry season and other prolonged dry periods. The very low runoff coefficients of the current plot-scale results in the same catchment demonstrates that the inverse relationship between overland flow and contributing area can be marked even with relatively small changes in area. This tallies with the findings of van de Giesen et al. (2005), who recorded a decrease of 40–75% in overland flow from short (1.25 m) to long plots (12 m)." (lines 681-692)

B) COMMENTS OF REVIEWER #1

Comment: “The article is very well written on a novel research about hydrological processes at the plot scale in a sub-urban area. Not much research has been carried out world-wide on this type of environment which justifies publication of this study in Journal of Hydrology. The suggestions regarding improvements made by de two reviewers were taken into consideration satisfactorily. I consider that the changes introduced in this new version of the article are sufficient in order to publish it as it is.”

Response:

Thank you for the endorsement to publishing our manuscript in the Journal of Hydrology.

C) COMMENTS OF REVIEWER #2

Comment: “Reviewer #2 raised the issue about connection between development and forest hydrology, and suggested that this should be deemphasized as the text does not point to any concrete connections. I found what the authors presented in the paper at best tangentially relevant to resolving this issue. For example, it appears from the text that the ratio of overland runoff to precipitation is quite low, even in the dense eucalyptus forest. If so, what makes the author think that eucalyptus forest would be a credible contributor to the 2006 flooding event? The authors stated in the introduction

"Thus, it is argued that forest cover might not significantly reduce peak flows during extreme events, particularly in small catchments"

This point was not explicitly investigated in the analysis. For the Oct event, I'm curious what the runoff to rainfall ratio is for the entire watershed? Normally the runoff ratio is a lot higher that what is observed over a patch. My own field experience indicates that overland runoff upstream may well reinfiltrate prior to reaching the stream, and much of the streamflow can be from shallow interflow.”

Response:

The mentioned statement provided in the Introduction section as regards to forest cover impact on peak flows was not performed by current manuscript authors, but rather a reference to Bathurst et al. (2011) conclusions. Nevertheless, in order to de-emphasize the peak flow issue, the paragraph was rewritten, without considering the above mentioned sentence:

> “Although it is widely accepted that forests regulate water yield and reduce the size of most streamflow responses to rainfall because the high permeability of their soils (Eisenbies et al., 2007; Bathurst et al., 2011), the role of forest areas in flood protection in extreme rainfall events has been hotly debated. Some have argued that interception and higher soil moisture deficits (of deeper, more porous and drier soils) under forest should reduce floods by removing a proportion of the storm rainfall (e.g. Bathurst et al., 2011), whereas others have argued that such water retention by forest is minimal in the extreme rainfall events that are responsible for floods (Eisenbies et al., 2007; Hümann et al, 2011; Komatsu et al., 2011).” (lines 98-106)

As correctly mentioned, current manuscript does not investigate the role of woodland areas on peak flows. Nevertheless, the authors would like to stress that the minor runoff coefficients measured over the 2-years period, represent the woodland response (although at plot scale) to relatively low storms. In order to emphasise this idea, a new sentence was added within the Rainfall sub-section of the Results and Analysis:

> "In total there were 333 days with rain during the 2-year monitoring period, with 47 daily falls exceeding 10.0 mm, of which four exceeded 25.0 mm. The highest daily falls were 48.1 mm on 14th December 2012, 43.1 mm on 7th March 2013, 29.0 mm on 19th January 2013 and 26.8 mm on 2nd November 2011. These falls are well below 102 mm fall recorded on 25th October 2006, which led to floods within the catchment." (lines 276-280)

Although minor, the temporal patter of runoff plots showed greatest values in late summer for dense eucalypt (due to hydrophobicity) and greatest values in late winter for sparse eucalypt and oak woodland (due to soil moisture), as a result of relatively small rain storms. Thus, it may be expected that runoff response can be bigger under extreme storm events, as discussed by other authors (e.g. Bathurst et al., 2011; Eisenbies et al., 2007).

As the reviewer stated, and as discussed on lines 683-69 of current manuscript, overland flow amount tend to decrease over larger slopes due to increasing infiltration and/or surface retention opportunities. However, under extreme events this may not be enough to prevent overland flow, as argued by previous authors (Eisenbies et al., 2007; Hümann et al, 2011; Komatsu et al., 2011).

Under extreme storms, even if overland flow from woodland areas may not have a significant contribution to catchment discharge, any additional overland flow going to downslope urban areas may be a problem. Thus, greater woodland responses to extreme storm events is an important issue particularly in peri-urban catchments, reason why the authors would like to stress the possibility of an increasing overland flow contribution, although the woodland response to extreme storm events, such as the October 2006 flooding event, was not measured. Furthermore, at the time of 2006 flooding event, catchment discharge was not being measured, so there is no available information on catchment runoff coefficient.

In order to better present this idea, the manuscript was revised as follow:

> "Giesen et al., 2005; Mounirou et al., 2012). In *Ribeira dos Covões*, considering the small amounts of overland flow generated under woodland land-use even for relatively small runoff plots, it can be concluded that the generation in woodland areas of sufficiently continuous overland flow able to reach valley floors and channels would be rare. It would also suggest that patches of all three types of woodland could act as sinks for overland flow generated on upslope impervious urban surfaces.
>
> The question remains, however, about overland flow responses in rainfall events more extreme than those recorded in the two-year study. The highest daily rainfall recorded in the monitoring period was only 48 mm, which is less than a 2-year return period event (Brandão et al., 2001). On 25th October 2006, however, following a period of very wet antecedent weather, a daily rainfall of 102 mm was recorded at Bencanta-Coimbra with a maximum hourly intensity of 56 mm leading to major flooding of the *Ribeira dos Covões*. According to Brandão et al. (2001), daily rainfall events of 94 mm and 112 mm at Coimbra have return periods of 10- and 50-years, respectively. The contribution from woodland areas to the 2006 flood is unknown and can only be surmised. As the 25th October rainstorm followed a prolonged period of wet weather,

it is highly likely that even in the dense eucalyptus the soil would have been largely hydrophilic and any overland flow generated in all three woodland types would probably have been saturation-excess in type. It is clearly possible that in such an extreme event the percentage saturation overland flow generated from all three woodland areas would have been much greater than the maxima of <3% recorded in the current study. Also a greater proportion would have been transferred to downslope areas, since surface water retention capacities provided by litter and micro-topographic concavities would have been exceeded. Although some studies have emphasized the limited storage capacity of forested terrain during larger storms and its minor role in flood protection (Bathurst et al., 2011; Eisenbies et al., 2007), it is considered that the high infiltration capacities of the soils of the catchment when hydrophilic (Ferreira et al., 2015) and the high storage capacities of the comparatively deep (>3m) sandstone soils of the dense and sparse eucalyptus sites would have limited the overland flow contribution from the eucalyptus woodland areas and retained some sink role for urban runoff, with really high percentages of overland flow restricted to the oak woodland areas with their shallow, easily saturated soils. It is arguable, however, that the overland flow contribution from the dense eucalypt areas would have been much higher if an extreme storm of the magnitude of the 25th October 2006 event had occurred after dry antecedent weather when the dense eucalyptus soil would have been highly hydrophobic rather than hydrophilic. Clearly the timing of extreme events in relation to woodland and soil types in a peri-urban catchment is of crucial significance to the size of overland flow responses and degree of downstream flooding." (lines 708-746)

Differences in overland flow, hydrophobicity and soil moisture dynamics between Mediterranean woodland types in a peri-urban catchment in Portugal

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Abstract

Forest hydrology has been widely investigated, but the impacts of different woodland types on hydrological processes within ~~-~~a peri-urban catchment mosaic~~s~~ are poorly understood. This paper investigates overland flow generation processes in three different types of woodland~~hardwood stand~~ in a small (6.2 km^2) catchment in central Portugal that has undergone strong urban development over the past 50 years. A semi-natural oak stand and a sparse eucalyptus stand on partly abandoned peri-urban land and a dense eucalyptus plantation were each instrumented with three 16 m^2 runoff plots and 15 throughfall gauges, which were monitored at c. 1- to 2-week intervals over two hydrological years. In addition, surface moisture content (0-5cm) and hydrophobicity (0-2cm, 2-5cm and 5-10cm) were measured at the same time as overland flow- and throughfall~~after individual rainfall events~~. Although all three woodland types produced relatively little overland flow (< 3% of the incident rainfall overall), the dense eucalypt stand produced twice as much overland flow as the sparse eucalypt and oak woodland types. This contrast in overland flow can be attributed to infiltration-excess processes operating in storms following~~during~~ dry antecedent weather ~~conditions~~ when severe hydrophobicity was widespread in the dense eucalypt plantation, whereas it was~~ as opposed to being~~ of moderate and low severity and less widespread in the sparse eucalypt~~ plantation~~ and ~~the~~ oak woodlands~~stand~~, respectively. In contrast, under wet conditions ~~more~~greater (albeit still small) percentages of overland flow ~~(though still small) tended to be~~ were produced in ~~the~~ oak woodland than in the two eucalypt plantations; this was probably linked to saturation-excess overland flow being generated more readily at the oak site as a result of its shallower soil. Differences in water retention in surface depressions affected overland flow generation and downslope flow transport. Implications of the seasonal differentials in overland flow generation between the

three distinct woodland types for the hydrological response of peri-urban catchments are addressed.

Keywords: Eucalypt plantations, oak woodland, saturation-excess overland flow, infiltration-excess overland flow, hydrophobicity, soil moisture content.

1. Introduction

Forest covers 31% of the world’s land surface (FAO, 2010) and 35% of mainland Portugal (ICNF, 2013). ~~In recent decades, g~~Globally forest cover has increased in recent decades as a result of greater demand for timber and environmental concerns (e.g. Robinson et al., 2003). However, ~~forest cover has decreased~~ in peri-urban catchments located in previously forested terrain, forest cover has decreased where urbanization has led to progressive deforestation and forest fragmentation (Nowak, 2006) and remaining woodland can often change in character because of altered or abandoned~~ment of~~ management.

Forest hydrology has been widely documented, particularly with respect to some hydrological processes. Interception has been measured and modelled for many forest stands, indicating differences linked to distinct canopy architectures and~~,~~ woody matter and leaf characteristics and biomass~~stem properties and root systems~~ (Muzylo et al., 2009; Rao et al., 2011). As a result of these factors (and climatic factors, notably rainstorm size distribution), ~~Interception affects rainfall partitioning and its redistribution, with~~ throughfall varies greatly between forests, typically from~~accounting for~~ 65 to~~–~~90% of precipitation, with~~hile~~ stemflow generally varying from zero to 15 %~~represents only a~~

~~minor fraction at 5-15%~~ (Herwitz and Levia, 1997; Crockford and Richardson, 2000; Wei et al., 2005). Differences in these processes can affect soil moisture distribution (Savva et al., 2013; He et al., 2014) and overland flow generation. Partly because overland flow is often considered a minor component of forest hydrology (Eisenbies et al., 2007; Gomi et al., 2008), ~~relatively~~ few studies have focused on differences in overland flow between~~the varying impact on overland flow of~~ different forest types, and in particular~~ly~~ between unmanaged, often abandoned woodland~~semi-natural~~ types affected by ~~the~~ peri-urbanization process and ~~compared with~~pre-existing managed forest plantations.

Hydrophobicity, induced by substances (especially some resins and waxes) produced by some vegetation species (Dekker and Ritsema, 1994), has become increasingly recognized as an important soil property that can affect overland flow in forest soils, particularly in seasonally dry environments. Thus in a ~~previously rip-ploughed~~ eucalypt plantation area of north-central Portugal, temporal changes in hydrophobicity ~~was~~ were found to explain 74% of overland flow variation (Ferreira et al., 2000). ~~Hydrophobicity is induced by various hydrophobic compounds, such as distinct resins and waxes, which restrict infiltration into soils (Dekker and Ritsema, 1994).~~ Many studies have demonstrated differences in degrees of hydrophobicity between different vegetation types (e.g. DeBano, 2000; Zavala et al., 2009; Lozano et al., 2013). Eucalypt stands are renowned for inducing high levels of hydrophobicity (Doerr et al., 1996; Ferreira et al., 2000; Santos et al., 2013), with~~. In Portugal,~~ some studies in Portugal~~have~~ ~~report~~linking~~ed~~ greater overland flow produced under eucalypt than pine plantations ~~caused by~~ with enhanced soil hydrophobicity under eucalyptus (Ferreira et al., 2000; Keizer et al., 2005). In contrast, ~~but~~ little is known about ~~the~~ overland flow in~~processes of~~ Mediterranean oak stands~~, particularly in wet Mediterranean climates~~. This is important as differences in overland flow between distinct forest stands can contribute to variations in total streamflow and the stormflow component with forest land-use change (Fritsch, 1993; Grip et al., 2005),~~. However, in the literature,~~ whereas in many cases streamflow differences in areas subject to forest species~~cover~~ change~~s~~ are ~~mostly~~ attributed to evapotranspiration adjustments (e.g. Swank and Douglass, 1974; Otero et al., 1994). ~~For example, Otero et al. (1994) reported reduced streamflow in Chile with conversion of native forest to fast-growing plantations of *Pinus radiata*. In the southern Appalachians, the conversion of a deciduous hardwood catchment to a *Pinus strobus L.* stand (eastern white pine), led to a 20% reduction of streamflow, attributed to the greater vegetative surface area of *Pinus strobus* (Swank and Douglass, 1974).~~

Although it is widely accepted that forests regulate water yield and ~~andand~~ reduce the size of most streamflow responses to rainfall because the high permeability of their soils ~~are usually highly permeable~~ (Eisenbies et al., 2007; Bathurst et al., 2011), the role of forest areas in flood protection in extreme rainfall events has been hotly debated. Some have argued that interception and higher soil moisture deficits (of deeper, more porous and drier soils) under forest should reduce floods by removing a proportion of the storm rainfall (e.g. Bathurst et al., 2011), whereas others have argued that such water retention by forest is minimal in the extreme rainfall events that are responsible for floods (Eisenbies et al., 2007; Hümann et al, 2011; Komatsu et al., 2011),~~. Thus,According to Bathurst et al. (2011)it is argued that forest cover might not significantly reduce peak flows during extreme events, particularly in small catchments, but that it could be effective in reducing the peakflow responses of more frequent, less intense rainfall events (Bathurst et al., 2011).~~

Impacts of different forest and woodland stands on overland flow may be particularly important in the hydrology of small peri-urban catchments, as they ~~. Such catchments~~

are~~tend to be~~ often characterized by a mosaic of different urban and non-urban land-uses, including woodland types on areas of altered or abandoned forest or agricultural management, as well as patches of pre-existing managed forest. Theoretically in such catchments, patches of forest types with permeable soil –can break flow connectivity over the landscape and act as sinks to overland flow from upslope urban surfaces, whereas any overland flow generated on forest types with soils of lower permeability may reach downslope urban surfaces and represent an additional contribution to the urban flood hazard.,~~–~~ Such peri-urban situations, particularly in areas of Mediterranean climate, have been little studied~~.~~ ~~which provide varying sources and sinks of overland flow~~ (Ferreira et al., ~~2011~~2015).

This paper investigates the influence of three different types of woodland occurring within a peri-urban mosaic on overland flow generation in the *Ribeira dos Cov~~o~~ões* catchment in an area of Mediterranean climate in central Portugal. –Two of the woodland types investigated ((i) sparse eucalyptus adjacent to eucalyptus plantations and (ii) oak woodland) have been strongly influenced by semi-abandonment of land with peri-urbanization, whereas the third comprises pre-existing managed dense eucalyptus. A previous investigation in the same catchment (Ferreira et al. (2015)~~ investigat~~assessed temporal changes ~~differences o~~in soil properties (soil matrix infiltration capacity, soil moisture content and ~~,~~ hydrophobicity~~ and soil matrix infiltration capacity)~~ at a network of points in different landscape units found in the ~~found in a Portuguese peri-urban~~ catchment (woodland-sandstone, woodland-limestone, agriculture-sandstone, agriculture-limestone, urban-sandstone and urban-limestone)~~,~~; it then~~ and~~ discussed their potential impacts on overland flow within the catchment~~processes~~. Results suggested ~~highlighted~~ that woodland areas might~~can~~ provide important sinks of overland flow during wet periods due to the high~~great~~ infiltration capacities recorded on their soils~~y~~, but might~~also~~ act ~~contribute~~ as overland flow sources in storms following~~during~~ dry periods (especially in summer) because of the hydrophobic nature of the soil matrix. The current paper tests these tentative suggestions of the previous paper by using a plot-scale monitoring approach to assess temporal differences in overland flow generation, and its influencing factors, between the sparse eucalyptus, oak woodland and managed dense eucalyptus woodland types over a two-year period. The focus is on the roles played by differing temporal regimes in hydrophobicity and soil moisture of the three woodland types studied. The implications of the results for planning land-use mosaics in peri-urban catchments in such environments are also explored.

~~Any overland flow generated on forest areas may reach downslope urban areas and represent an additional contribution to the urban flood hazard, whereas in other cases forest patches can break flow connectivity over the landscape and prevent overland flow to reach downslope urban areas. act as sinks for upslope-generated overland flow from urban surfaces. Knowledge of overland flow responses from different forest and woodland types is arguably important for land-use planning and water resources management of catchments undergoing partial urban development.~~

~~Based on Ferreira et al. (2015), tThis paper further investigates the role of woodland areas on overland flow processes. Temporal differences in overland flow generation, and its influencing factors, in distinct sparse eucalypt (on land adjacent to eucalyptus plantations) and oak woodland types, as well as on managed dense eucalyptus plantation forest, were addressed in a peri-urban catchment in central Portugal, using a plot-scale monitoring~~

~~approach over a two-year period. The focus is on the roles played by differing temporal regimes in hydrophobicity and soil moisture of the woodland types studied.~~

~~The implications of the results for streamflow response in peri-urban catchments in such environments are also explored.~~

2. Study area

The study was carried out in the peri-urban *Ribeira dos Covões* catchment (8º27´W, 40º13´N), located 3km NW of Coimbra, the largest city in central Portugal. The~~is~~ catchment (Figure 1) is ~~(~~6.2km^2~~)~~ in area, is aligned S-N and ranges in altitude from 34 to 205 m a.s.l. The area has a ~~sub-humid~~ Mediterranean climate, with a mean annual temperature of 15°C and an average annual rainfall of 892 mm over the period 1941-2000 recorded at Coimbra-Bencanta (national meteorological weather station 12G/02UG), sited 0.5 km north of the study catchment. A ~~distinct~~ dry and hot season occurs from June to August (8% of annual rainfall), whereas the rainiest period is from~~between~~ November to~~and~~ March (61% of annual rainfall). ~~Relatively small r~~Rainfall events are mostly small~~dominant over the year~~, with 83% of daily rainfalls in 2001-13~~between 2001 and 2013~~ at Coimbra-Bencanta being ≤~~<~~10 mm. Annual m~~M~~aximum daily rainfalls in~~over the same~~ 2001-13 ~~period~~ ranged from~~between~~ 20 mm to~~and~~ 102 mm. The catchment is underlain by sandstone (57%) and limestone (43%). Soils developed on sandstone are classified as Fluvisols and Podsols, following the WRB (2006) classification, and are generally deep (>3 m), while the Leptic Cambisols found on limestone slopes are typically shallow (<0.4 m) (Pato, 2007).

The catchment has undergone profound land-use changes over the last five decades, mainly associated with ~~rapid~~ urbanization and planting of~~increased~~ eucalyptus~~ planting~~ for timber production. Between 1958 and 2007, the urban area expanded from 6% to 32% and woodland ~~areas~~ expanded from ~~6 to 32% and from~~ 44% to 64%, ~~respectively,~~ at the expense of a marked decrease in agricultural land from 48 to 4%. Since 2007, further urbanization has occurred mainly through deforestation. Thus by 2012, the urban area had increased to 40%, while the increasingly fragmented woodland area had decreased to 53% (Figure 1).

Currently, the woodland area consists mainly of *Eucalyptus globulus* Labill. plantations (55%), but with some mixed stands of eucalypt and pine (29%), scrubland~~s~~ (15%) and relict oak woodland composed of *Quercus robur L.*, *Q. faginea broteroi* and *Q. suber L.* trees (1%) (Figure 1). Generally, eucalypt plantations occur on sandstone, but some areas, abandoned following logging, are now covered by sparse eucalypt stands with a dense scrub understorey. On limestone, vegetated areas are largely covered by shrubs (e.g. *Pistacia lentiscus*, *Spartium juncium*, *Cistus crispus*, *Ulex jussiaei*), but with semi-natural oak stands. In the oak area, a number of stone walls have survived from an earlier agricultural land-use, mainly olive plantations. Thus both the sparse eucalyptus and oak woodland types have been strongly influenced by semi-abandonment of land with peri-urbanization.

3. Methodology

3.1 Experimental design and measurements

Three runoff plots were established in each of the three principal types of woodland within the *Ribeira dos Covões* catchment (Figure 1): (1) dense eucalypt plantation, which contains~~may include~~ occasional pine and acacia trees (plots DE1, DE2 and DE3); (2) sparse eucalypt areas, with an extensive cover of scrub (SE1, SE2 and SE3); and (3) oak woodland (O1, O2 and O3). The spatial distribution of woodland types within the catchment and site accessibility led to topographic and lithological (and hence soil) differences between the three study sites (Table 1). Eucalypt plantations, as they overlie sandstone, exhibit a sandy-loam soil ~~o~~in dense plantations, but a loamy sand soil in sparse stands, whereas the oak woodland is located on limestone and has a loamy soil.

The three runoff plots at each study location were placed 20 – 500 m apart, depending on local constraints (e.g. avoiding close proximity to tracks and locations with extensive stone lag). The plots were ~~2m wide by ~~8m long by 2m wide and were bounded by 15cm high metal strips (inserted into the soil to a depth of 5-10cm).Each plot was connected to a modified Gerlach trough to collect~~retain~~ eroded sediment and thence~~, subsequently,~~ to a tipping-bucket device and a 50-litre tank for ~~collecting and~~ recording and collecting the overland flow. Plot installation was completed on 10th January 2011, but data collection started one month later, in order for the plots to recover from any disturbance caused during installation.

Each plot was further equipped with five manual throughfall gauges to give an approximate idea of differences between woodland types. The throughfall gauges comprised funnels (20 cm in diameter) connected to a storage bottle (3-litre capacity), installed at the soil surface within half-buried PVC pipes (20 cm in diameter and 30 cm long). The five gauges were placed randomly 0.5-2m outside the plot boundaries beneath the tree and/or scrub vegetation. Rainfall data were based on weighted-average results of five tipping-bucket rain gauges installed in open areas within and near the catchment (Figure 1). Given the relatively small number of throughfall gauges, throughfall measurements only represent exploratory data to give a comparison between woodland types; ~~and~~ water inputs to the plots were based on rainfall data.

Hydrophobicity and soil moisture content were measured on undisturbed land adjacent to each plot. Soil hydrophobicity was assessed at 0-2 cm, 2-5 cm and 5-7 cm depths along two 1-m transects at either side of each plot using the 'Molarity of an Ethanol Droplet test' (Doerr, 1998). Sets of fifteen droplets of increasing ethanol concentration were applied along each transect until infiltration of at least eight droplets of the same concentration occurred within 5 seconds. The results for each transect were classified according to the following five repellency ratings and associated ethanol concentrations: wettable (0%); low (1, 3 and 5%); moderate (8.5 and 13%); severe (18 and 24 %); and extreme (36 and >36 %) hydrophobicity. Gravimetric soil moisture content was determined in the laboratory by oven-drying at 105ºC for 24h. On each measurement occasion, this was done using one composite soil sample per plot (0-5cm soil depth), which was obtained by mixing 10 samples collected randomly on undisturbed land around each plot. Gravimetric was converted into volumetric water content using the mean soil bulk density of each site, calculated from 11 random soil samples of –143 cm^3 volume collected near to each plot, using purpose-built soil ring samplers of 5 cm diameter and 7.3 cm length.

Overland flow, throughfall, hydrophobicity and soil moisture were measured on 61 occasions at 1- to 2-week intervals (depending on previous rainfall) over the ~~two~~ 2-years from 9th February 2011 to 14th April 2013. In March 2012, part of the dense eucalypt site was clear-felled, destroying plot DE2 (where monitoring was abandoned) and affecting tree interception at plot DE1. Owing to vandalism and theft of equipment on several occasions after clear-felling, throughfall measurement at the dense eucalypt plot locations was also abandoned from mid-2012 onwards.

3.2 Data analysis

In view of the non-normal distribution of the overland flow, throughfall, soil moisture and hydrophobicity data, non-parametric statistical tests were used to assess differences in median values between the three woodland types and between plots of the same woodland type. The Kruskal–Wallis test was employed to test the significance ($p<0.05$) of the differences with woodland type in overland flow, throughfall, hydrophobicity and soil moisture, and their seasonal variations. The statistical significance of differences in medians between seasons/plots/stands was assessed using the Least Significant Difference (LSD) test. The Spearman correlation coefficient (r) was used to assess whether significant associations ($p<0.05$ and $p<0.01$) existed between rainfall characteristics (1- to 2-weekly totals, maximum 30-min rainfall intensities (I_{30}) and 30-day antecedent rainfall) and soil hydrological properties (hydrophobicity and soil moisture), as well as overland flow. All statistical analyses were carried out using IBM SPSS Statistics 22 software.

4. Results and Analysis

4.1 Rainfall

Overall, rainfall over the 2-year monitoring period (totalling 1581.7 mm) was relatively low~~dry~~, with annual rainfalls in 2011 and 2012 being 18 and 38% respectively below the long-term (1941-2000) average of 892 mm. The 61 measurement periods differed markedly in total rainfall amount (1.8-113 mm) (Figure 2), number of rainfall days (2-12) and maximum 30-min rainfall intensity (I_{30}: 0.6-24.8 mm h^{-1}), but none represented extreme rainfall events (all beneath 2-years Intensity-Duration-Frequency curves for~~of~~ Coimbra (Brandão et al., 2001). The seasonal pattern was typically Mediterranean, with distinctly lower rainfall in summer (4% of total rainfall fell in June to August) compared with 35% in autumn, 32% in winter and 28% in spring. Nevertheless, there was also a very dry period in winter 2011/12 from 21st December 2011 to 20th March 2012 (37 mm). In contrast, November 2011, January 2013 and March 2013 were wetter than the long-term 1941-2000 averages ~~(1941-2000)~~ (163 vs 111 mm, 166 vs 116 mm and 228 vs 87 mm, respectively). In total there were 333 days with rain during the 2-year monitoring period, with 47 daily falls exceeding 10.0 mm, of which four exceeded 25.0 mm. The highest daily falls were 48.1 mm on 14th December 2012, 43.1 mm on 7th March 2013, 29.0 mm on 19th January 2013 and 26.8 mm on 2nd November 2011. These falls are well below 102 mm fall recorded on 25th October 2006, which led to floods within the catchment.

4.2 Throughfall

Although ~~it should be stressed that~~, given the small number of gauges, assessments were only exploratory, throughfall for the period 2nd April 2011 to 5th March 2012 (periods 3-23), when measurements were carried out at all three woodland sites, was higher in dense eucalypt (92% of rainfall) than in sparse eucalypt (87%) and oak stands (82%) (Figure 2).

For the 2-year period 2nd April 2011 to 14th April 2013 (periods 3-61), however, overall throughfall percentages were rather higher (~~represented~~ 97% and 92% of rainfall in the sparse eucalypt and oak stands respectively. In both periods, ~~no significant~~ differences ~~was identified~~ in percentage throughfall between woodland types were found to be not statistically significant ($p>0.05$).

Throughfall percentages increased significantly with rainfall amount and maximum intensity ($r=0.83$ and 0.57, respectively; $p<0.01$). Generally throughfall percentages for measurement periods were lower in summer ~~dry~~ than winter~~et periods~~, with median values of 90%, 74% and 46% in summer, and 93%, 92% and 86% in winter, for dense eucalypt, sparse eucalypt and oak stands, respectively. No throughfall was recorded for rainstorms of less than 3.7 mm following antecedent dry weather (e.g. periods 10 and 34).

4.2 Hydrophobicity

In all soil layers, hydrophobicity was most severe and frequent in the dense eucalypt plantations, intermediate in the sparse eucalypt stand and least~~owest~~ in the oak woodland ($p<0.05$) (Figure 3). In the oak stand, hydrophobicity was absent on many measurement dates (69% of occasions at both 0-2 cm and 2-5 cm and 48% of occasions at 5-7 cm) and was largely of low or moderate severity when present. In this woodland type, hydrophobicity was mainly transient in nature, being recorded in all the sampling sites only on 14%, 13% and 17% of monitoring occasions, at 0-2 cm, 2-5 cm and 5-7 cm depth, respectively. In the sparse eucalypt site, hydrophobicity showed the greatest spatial and temporal variation; hydrophilic conditions were dominant on 49%, 34% and 39% of the measurement dates, at 0-2 cm, 2-5 cm and 5-7 cm, respectively, but hydrophobicity was mostly moderate to severe ~~-~~when present. As in oak woodland, the sparse eucalypt stand showed a transient and patchy hydrophobic pattern, with widespread hydrophobicity recorded ~~i~~on just 26% of the 61 measurement occasions~~periods~~ at 0-2 cm and 5-7 cm and on 24% of occasions at 2-5 cm depth. In contrast, in dense eucalypt plantations, hydrophilic conditions were only observed on 41%, 15% and 13% of occasions, at 0-2 cm, 2-5 cm and 5-7 cm depth respectively, with severe to extreme hydrophobic properties being dominant and widespread~~, forming a continuous surface area~~ on 53%, 55% and 70% respectively of occasions when hydrophobicity was present.

Hydrophobicity showed the same marked seasonal pattern at all three study sites. It was typically absent during late autumn and winter, and most severe and widespread during summer. After dry periods, hydrophobicity was more resistant to being broken down during rainfall events in eucalypt plantations and disappeared earlier in oak woodland. Also, hydrophobicity was re-established more quickly in dry periods under eucalypt than under oak. Thus after the largest rainfalls in autumn 2011 and beginning of winter 2012, hydrophobicity required five months longer to reappear in oak than in the eucalypt stands.

In dense eucalypt stands, hydrophobicity increased in frequency and severity with soil depth (differences between 0-2 cm and 5-10 cm layers, $p<0.05$). Also, ~~a greater number of~~more rainstorms were required to reduce hydrophobicity levels in deeper soil. Extreme hydrophobicity was recorded on 18%, 13% and 30% of occasions respectively at 0-2 cm, 2-5 cm and 5-10 cm. A similar pattern with depth occurred ~~in~~at the sparse eucalypt site, despite lower hydrophobicity severity and coverage (extreme hydrophobicity was recorded ~~i~~on 8%, 13% and 15% of occasions, at 0-2 cm, 2-5 cm and 5-10 cm depth, respectively). In contrast to eucalypt sites, hydrophobicity did not vary significantly with soil depth in oak woodland (p>0.05), although it showed a tendency to decrease in severity but increase in temporal frequency with soil depth (Figure 3).

Although hydrophobicity severity and spatial frequency varied with antecedent weather at all sites~~tands~~ and at all depths in all woodland types, inverse relationships with storm rainfall and throughfall amount, although statistically significant (p<0.01), are weak (*r* never exceeding -0.31) and are not statistically significant in the case of maximum rainfall intensity (p>0.05) (Table 2).

4.3 Soil moisture content

Median surface soil moisture content (0-5 cm depth) over the two-year period was similar in dense (15%) and sparse (18%) eucalypt stands (p>0.05), but significantly higher at oak sites (29%) (p<0.05) (Figure 4).

Soil moisture content increased significantly with preceding period rainfall amount and throughfall (p<0.01), although ~~the~~ relationships were not very strong (Table 2). It was substantially lower in summer than in other seasons (p<0.05), with a similar median value (8%) for all woodland types. Soil moisture was much higher in autumn, winter and spring ~~increased slightly from spring, to autumn and winter~~ (~~21,~~ 24%, ~~and~~ 25% and 21%, respectively), but with variations between ~~the two~~ years. During spring, median soil moisture content was higher in 2013 (22%) than in both 2011 (16%) and 2012 (11%) (p<0.05). In autumn, soil moisture was significantly higher in 2011 than in 2012 (28% vs 17%) (p<0.05). In winter, median soil moisture reached highest values in 2013 (26 % compared with 19% in 2011 and 20% in 2012). Generally, higher soil moisture content was observed during autumn 2011 (median values of 27%, 33% and 27% for ED, EO and O, respectively), winter 2013 (median values of 23%, 24% and 36% for ED, EO and O, respectively) and spring 2013 (median values of 18%, 22% and 36% for ED, EO and O, respectively). Soil moisture content reached highest values of 37%, 32% and 49% in ED, EO and O in winter 2013, but the peak value of 47% in the EO site was attained in autumn 2011.

Generally, soil moisture content showed strong and statistically significant inverse correlations with hydrophobicity (*r* ranged between -0.42 and -0.52 for different soil depths, p<0.01, Table 2). It was also significantly affected by soil properties, such as particle size distribution and bulk density, as well as slope gradient, although correlations coefficients were rather low~~weak~~ (Table 2).

4.4 Overland flow

The median plot values of overland flow amount in mm (above) and as a percentage of rainfall (below) for each woodland type in each of the 61 measurement periods is shown in Figure 5. Although ~~O~~overland flow was generated in most measurement periods (97, 92 and 89% of ~~the~~ occasions for dense eucalypt, sparse eucalypt and oak stands, respectively), ~~although runoff over the 2 years overall runoff coefficients represented less than 1% of total rainfall over the 2 years (Figure 5). O~~median overland flow exceeded 1% of period rainfall on just 8, 4 and 3 occasions out of 61 for dense eucalypt, sparse eucalypt and oak sites, respectively, and never exceeded 3% (Figure 5). Overland flow amounts (median values for individual periods), ~~was~~ were significantly higher in the dense eucalypt plantation than in the sparse eucalypt and oak stands (p<0.05, Kruskal-Wallis and LSD tests) and overland flow over the two-year period was over twice as high in dense eucalyptus (6.9 mm, 0.43%) than at the sparse eucalyptus (2.6 mm, 0.16%) and oak woodland (2.9 mm, 0.18%) plots. ~~(median overall values of 6.9 mm, 2.6 mm and 2.9 mm, respectively, over 2 years)~~ ~~(p<0.05).~~

Differences in the temporal pattern of overland flow were also observed between woodland stands. Dense eucalypt plantation plots generated greater percentage overland flow (medians of up to 2.2%) in rainstorms occurring after dry antecedent weather~~in dry settings~~ (especially in late spring, summer and at the beginning of autumn), whereas in wet conditions, even in large events, it never exceeded 1.0 %.~~was lower than 1.0%~~. In the sparse eucalypt stand, median overland flow varied in contrary fashion~~less~~ over the year, with higher values in wet weather of autmn, winter and spring and lower values in storms following dry periods, particular in summer and early autumn. Thus the maximum~~maximum greatest~~ recorded median runoff coefficient~~s~~ ~~of~~ was only 0.~~5~~4% ~~-~~in a measurement period after dry weather ~~in dry~~ but~~and~~ 1.~~2~~3% after wet weather~~in wet settings~~. ~~. (mainly in spring, autumn and winter periods).~~ In the dense eucalypt plantation, the highest percentage overland flow values were recorded in moderate rainfall events (4-23 mm and I_{30}= 3-16 mm h^{-1}), whereas in the sparse eucalypt stand highest percentage overland flow occurred in relatively small rainfall events (4-10 mm and I_{30}=3-6 mm h^{-1}). Again, ~~I~~in contrast to the dense ~~both~~ eucalypt plots~~sites~~, ~~overland flow~~ in oak woodland overland flow was mainly produced after the wettest antecedent weather and soil moisture conditions, attaining higher values mostly~~ainly~~ in larger rainfall events (>10 mm)~~, which were mostly experienced~~ in winter and spring 2013, the wettest ~~measurement periods in~~part of the 2-year study. In the oak woodland, however, ~~Even under the wettest conditions, however, the highest recorded runoff coefficient only reached 2.2% in the oak stand (but~~

even in the wettest periods, median runoff coefficient values of the three replicated plots never~~did not~~ exceeded 0.6%~~)~~ and~~,~~ ~~whereas~~ following dry weather both median and individual plot runoff coefficients never~~it did not~~ exceeded 0.4%.

Under dense eucalypt plantation, overland flow ~~did not~~ varied little~~y much~~ between runoff plots, ~~even after clear-felling (p>0.05),~~ except immediately after clear-felling~~disturbance~~ at one of the plots ~~(results not shown)~~. Thus, the clear-felled plot (DE1) experienced its~~had the~~ highest runoff coefficient (2.3%) immediately after logging ~~(2.3%),~~ in late winter (period 22), but it was quickly reduced. Plots installed in sparse eucalypt and oak sites showed significant differences between plots (p<0.05) (results not shown). Thus ~~I~~in the sparse eucalypt stand, total overland flow over the ~~two~~2-year period was higher at SE3 (5.9 mm) than at SE1 (1.4 mm) and SE2 (2.9 mm).~~total overland flow over the 2-year period amounting to 5.9, 1.4 and 2.9 mm, respectively).~~ In ~~the~~ oak woodland~~site~~, overland flow was lower at O1 than at O2 and O3 (2-year totals of 1.9 mm, 4.3 mm and 3.2 mm, respectively).

Median ~~O~~overland flow amount increased significantly with period rainfall (amount and intensity) and throughfall (Table 2), but the strength of correlations varied with woodland type. Dense eucalypt plantation exhibited stronger correlations between overland flow and rainfall variables than the other woodland types (DE: *r*=0.61 and 0.62, SE: *r*=0.44 and 0.34, and O: *r*=0.53 and 0.27 for rainfall amount and I_{30}, respectively, p<0.01). Oak woodland showed stronger correlations than eucalypt plantations between overland flow and throughfall amount (r=0.48, 0.46 and 0.60 for DE, SE and O stands, respectively, p<0.01), as well as with 30-day antecedent rainfall (*r*=0.43 and 0.26 for O and SE, p<0.01, no significant correlation for DE).

Generally, overland flow amount from all the plots correlated significantly neither with hydrophobicity nor soil moisture content (p>0.05, Table 2).~~-~~ In the plots installed in oak woodland, as well as in~~ and~~ sparse eucalypt plantations, however, overland flow increased with soil moisture content, although correlation coefficients were weak (*r*=0.21 and 0.29, respectively, p<0.05).

5 Discussion

5.1 ~~Spatiot~~Temporal patterns of hydrological properties and woodland type

5.1.1 Throughfall

Despite the reported important role of vegetation structure and architecture in influencing throughfall amount (Návar, 1993; Levia and Herwitz, 2005; Levia et al., 2010; Livesley et al., 2014), no significant differences in exploratory throughfall data were identified between the different woodland types in *Ribeira dos Covões*. This may be due to different characteristics of the three types offsetting each other. Thus the larger scrub cover of the sparse eucalypt stand, which extended above throughfall gauges, may be the reason for its~~the~~ slightly lower throughfall (87%) than ~~that recorded~~ in the dense eucalypt plantation (~~87 and~~ 92%~~, respectively~~)~~,~~ with its limited underbrush cover (Table 1). ~~However, since~~As throughfall measurements were made ~30 cm above the soil surface, however, ~~actual~~ interception by scrub less than 30 cm high would be missed and actual throughfall would be smaller than the values recorded.

~~In *Ribeira dos Covões* the indicative throughfall percentages were generally in accordance with or higher than those reported in literature dealing with similar woodland stands~~. In eucalypt plantations in *Ribeira dos Covões*, the median throughfall of~~was~~ 92%, at the higher end ~~similar to~~ of the range of ~~higher throughfall~~ values (58-92%) reported by Valente et al. (1997) ~~under~~for *Eucalyptus globulus* Labill. stands elsewhere in Portugal ~~(58-92%), but~~ and higher than the values (85-88%) for the same species reviewed by Llorens and Domingo (2007).~~ under *E. globulus* (85-88%).~~ In shrubs and bushes (the dominant land cover under sparse eucalypt stand in the study catchment), a mean throughfall of about 49% has been reported (Llorens and Domingo, 2007). Despite, to the authors' knowledge, no throughfall measurements having been previously undertaken in *Q. robur, Q. faginea* or *Q. suber* (the forest species found in the oak stand within the catchment), the results from *Ribeira dos Covões* (median of 92%) are higher than those reported for *Q. cerris L.* (85-89%), *Q. pyrenaica*, (83-86%), *Q. coccifera* (55%) and *Q. ilex* (60-78%) (Llorens and Domingo, 2007).

The relationships found between ~~T~~throughfall ~~was found to be affected by~~and rainfall amount and intensity tallies with findings~~as reported in~~ of previous studies (e.g. Gash, 1979; Ferreira, 1996; Shachnovich et al., 2008; André et al., 2011). Smaller rainstorms (< 3.7mm) could have been fully or mostly~~partly~~ intercepted by vegetation (<3.7 mm), but with increasing storm rainfall and wet antecedent conditions, canopy storage exceedance leads to enhanced percentage throughfall values, as reported elsewhere (Gash, 1979; Crockford and Richardson, 2000; Eisenbies et al., 2007; Bathurst et al., 2011). This may explain the very high~~higher~~ throughfall in wetter measurement periods, ~~as well as the higher results~~such as ~~in the period~~ 2nd April 2011 - 5th March 2012, ~~than 2nd April 2011 – 5th March 2012,~~ which included some large rainstorm events.

5.1.2 Hydrophobicity

In *Ribeira dos Covões*, soil hydrophobicity was high and resistant to breakdown in eucalypt stands (particularly in the dense plantation), as widely reported previously (e.g. Doerr et al., 1996; Ferreira et al., 2000; Keizer et al., 2005; Keizer et al., 2008; Santos et al., 2013). In *Ribeira dos Covões*, however, hydrophobicity disappeared after 113 mm rain (period 11), whereas Ferreira et al. (2000) found hydrophobicity persisted after 200 mm rainfall in an area of schist soils farther north in Portugal. ~~Nevertheless, t~~The recorded increase in spatial extent (frequency) ~~the extension~~ and severity of hydrophobicity under eucalypt stands with soil depth, and the greater temporal variability at the soil surface than below it, ~~is in~~ accords~~ance~~ with the findings of Keizer et al. (2005) for similar plantations in the coastal zone of central Portugal. The increase in hydrophobicity with soil depth, however, contrasts with the findings of Santos et al. (2013) in similar plantations but on schist soils in Portugal. Two possible reasons for the increase with depth are: (1) hydrophobic exudates being leached and precipitated in the subsoil during storm events, as reported by Doerr et al. (2000); and (2) hydrophobic conditions at depth being enhanced by greater preferential flow and less water infiltrating permeating into matrix soil at depth than at the soil surface.

Under the oak woodland, the ~~observed~~relatively low severity and persistence of hydrophobicity recorded accord with the findings of Cerdà and Doerr (2005) for *Q. coccifera* in south-eastern Spain. However, the similar hydrophobicity found between soil depths in *Ribeira dos Covões* is in contrast to the progressive decrease described for oakwood soils in northeast Spain (Badía et al., 2013).

The recorded differences in hydrophobicity severity and persistence between woodland types in *Ribeira dos Covões* (dense eucalypt > sparse eucalypt > oak) may in part be linked to vegetation type and density, but could also be linked to soil texture differences. Hydrophobicity is more frequently associated with coarse- than fine-textured soils (DeBano, 1991; Cerdà and Doerr, 2007; Martínez-Zavala and Jordán-López, 2009) and can be reduced by small increases in clay content, depending on the clay type (McKissock et al., 2000). This could enhance the hydrophobicity on the sandier eucalypt locations on sandstone compared with the loamy oak woodland sites on limestone in the *Ribeira dos Covões* catchment.

The seasonal hydrophobicity pattern characterized by greater severity and spatial extent in dry periods, and lower under wet settings, has been widely reported elsewhere (Dekker and Ritsema, 1994; DeBano, 2000; Doerr et al., 2000; Ferreira et al., 2000; Keizer et al., 2005; Santos et al., 2013) and is clearly linked to the antecedent (including seasonal) rainfall pattern. The significant inverse correlations found between hydrophobicity and antecedent rainfall were also recorded by Buczko et al. (2007), but not by Santos et al. (2013) for other eucalypt sites in Portugal.

5.1.3 Soil moisture content

The higher soil moisture content recorded under oak than in the two eucalypt stands may be associated with higher water retention by the finer-textured soil overlying limestone bedrock compared with the coarser sandstone soils of the eucalypt areas. The higher soil moisture content under oak, however, could also ~~be the~~ result from ~~of~~: (1) more effective ponding by underlying bedrock in the shallower soil (<0.4 m on limestone as opposed to >3 m in sandstone), as found elsewhere ~~by~~ (Maeda et al., ~~(~~2006~~),~~; Hardie et al., ~~(~~2012~~)~~; ~~and~~ Yang et al., ~~(~~2012); (2) the lower slope angles of the oak woodland site (Table 1 ~~(13-22° as~~

~~opposed to 16-26º and 26-28º in dense and sparse eucalypt plots)~~, as ~~found~~ reported elsewhere by Zhu and Lin (2011); (3) the lower position of oak plots on the hillslope (Table 1), leading to more effective moisture accumulation and retention than upslope (Kim, 2009; Ridolfi et al., 2003); and (4) the presence of a few relict stone walls in the oak woodland which may have increased water retention, as ~~found~~ recorded elsewhere by Yang et al. (2012).

In order to assess the importance of topography, particularly the slope and upslope areas that can contribute with overland flow, on soil moisture differences between woodland types, Topographic Wetness Index (TWI) was calculated for the catchment area, using the method described by~~according with~~ Pei et al. (2010). Although in *Ribeira dos Covões* catchment TWI reaches 21, TWI values for the woodland plots do not exceed 5, highlighting the lower probability of saturation excess overland flow. Nevertheless, the differences in ~~soil saturation probability increases from sparse to dense eucalypt plantations and to oak woodland (~~TWI values ~~range~~ between the sparse eucalyptus (1-2)~~,~~ dense eucalyptus (2-3(and oak woodland plots (4-5)~~4-5 within the plots installed in the sparse eucalypt, dense eucalypt and oak woodland stands, respectively), which would~~ may explain the greatest soil moisture content being measured at the oak woodland sites.

~~In addition to differences in soil properties and terrain characteristics,~~ The higher soil moisture recorded under oak than eucalypt ~~sites~~ could also be linked to factors driven by vegetation, such as transpiration and hydrophobicity (less intense and less frequent in oak woodland soil). Daily transpiration from a mature *Eucalyptus globulus* Labill. stand in Portugal varied between 0.5 and 3.6 mm day^{-1} during a spring-summer period (David et al., 1997), although~~and~~ in south-eastern Australia, Forrester et al. (2010) reported transpiration rates in eucalyptus plantations varying from 0.4 mm day^{-1} in two-year-old stands ~~at age 2-years~~ to 1.6–1.9 mm day^{-1} in stands aged 5–7 years. Lower transpiration rates of 1,3 mm day^{-1} (464 mm a^{-1}-) and 1.2 mm day^{-1} 4(453 mm a^{-1} ~~(1.3 and 1.2 mm day^{-1}~~) were reported for *Quercus ilex* L., in Catalonia, NE Spain, in valley and ridge-top locations, respectively (Sala and Tenhunen, 1996).

In *Ribeira dos Covões*, the higher soil moisture content in oak than eucalypt stands, however, does not seem to result from greater water consumption by eucalypt trees, since no significant difference in soil moisture was found between dense and sparse eucalypt stands. Indeed the evapotranspiration rate of extensive scrub cover can be similar to that of eucalypt trees (Bellot et al., 2004; Hümann et al., 2011; Yang et al., 2012), which could account for~~lead to~~ the absence of significant soil moisture differences between the sparse and dense eucalypt stands. The high evapotranspiration provided by the scrub cover may also counterbalance the higher soil water retention expected at the sparse than dense eucalypt stands, due to higher silt and clay contents (Table 1).

Surface soil moisture content appears to be strongly associated with hydrophobicity pattern. Generally, soil moisture was low when hydrophobicity was most severe and high when hydrophobicity was weak or absent. In *Ribeira dos Covões*, hydrophobicity was absent above soil moisture contents of 33%, 21% and 32% in dense eucalypt, sparse eucalypt and oak woodland, respectively (Figure 6). Similarly, extreme hydrophobicity was not recorded for soil moistures above 26%, 18% and 21%, respectively, reinforcing the view of the highly resilient nature of hydrophobicity in dense eucalypt plantations. Differences in the critical moisture content for the existence of hydrophobicity between woodland types may be linked to variations in soil texture (Doerr et al., 2000) and soil organic matter (Tumer et al., 2005; Jordán et al., 2013), where the latter may be linked to species of trees and understorey vegetation. Previous studies have reported hydrophobicity for soil moisture contents of up to 22% in sandy loam soils (Doerr and Thomas, 2000), and as high as 38% in clayey soils (Dekker and Ritsema, 1994). Under eucalypt plantations in central Portugal, Santos et al. (2013) reported the dominance of strong and extreme hydrophobicity in schist soils when soil moisture content was below 14%, which is lower than for the sandstone and limestone findings in *Ribeira dos Covões* ~~findings~~.

5.1.4 Overland flow

Runoff plots installed in *Ribeira dos Covões* recorded very low overland flow coefficients (<3%) in all the woodland types~~sites~~. Generally, vegetation enhances infiltration, particularly in tree stands because of their comparatively deep root systems (Calvo-Cases et al., 2003; Hümann et al., 2011; Komatsu et al., 2011). Nevertheless, the underlying bedrock can also have an important effect on slope hydrology, particularly influencing infiltration and overland flow (Hattanji and Onda, 2004; Zhang and Hiscock, 2010). Generally, coarse-textured soils associated with sandstone are usually highly permeable, allowing water to drain freely. High permeability of limestone soils has been also widely reported in areas of Mediterranean climate (e.g. Calvo-Cases et al., 2003; Cerdà, 1997). Although bedrock differences in the study catchment may mask the influence of woodland type, significant overland flow differences were found between dense and sparse eucalyptus despite both being on sandstone, and no significant overland flow difference was identified between sparse eucalypt and oak stands despite the latter overlying limestone. Spatiotemporal variation in overland flow pattern between woodland types is thought instead to be a consequence of hydrophobicity differences, since no significant throughfall difference was found between woodland stands, and soil moisture was higher in oak soils, where overland flow was lower.

In storm events following dry weather, the most likely cause of overland flow seemed to be infiltration-excess caused by hydrophobic soils~~,~~, as suggested by previous surveys of point-scale hydrological soil properties in the catchment ~~by~~ (Ferreira et al. (2015). Thus the greater severity and persistence of hydrophobicity in the dense eucalypt plantation are considered to be the reasons for its greater overland flow percentages, especially in larger rainstorms following dry antecedent conditions. In the sparse eucalypt stand, the less severe and patchier hydrophobicity also broke down more easily as a result of rainfall (see section 4.2), thereby explaining the lower overland flow than in the dense eucalypt plantations. Nevertheless, smaller rainfall events (3.7 mm and 9.5 mm in period 23 and 25) failed to break down soil hydrophobicity in the sparse eucalyptus (Figure 3), which may explain the higher percentage overland recorded in those periods (Figure 6). In oak woodland, the low or moderate hydrophobicity and its much patchier nature would explain why infiltration-excess overland flow responses were very small even after prolonged dry weather. Differences in the breakdown resistance of hydrophobic properties may also be the reason for a stronger correlation between overland flow and rainfall in dense eucalypt plantation than in the other woodland types (see section 4.4).

Even under extreme hydrophobic conditions, however, overland flow was minor. Thus, the maximum average runoff coefficient at the dense eucalypt plots never exceeded 2.2%. This value is lower than the maximum of 10% measured in similar experimental plots in eucalypt stands in north-central Portugal following a long dry season, though for schist soils (Ferreira et al., 2000). The low overland flow under extreme hydrophobicity suggests the role of water sinks within the woodland soils. Given the relatively low soil moisture content of~~in~~ hydrophobic soils, infiltration would seem to occur: (1) in hydrophilic soil patches, linked to a discontinuous hydrophobic layer, particularly under oak and sparse eucalypt stands (Figure 3); and (2) via preferential flow routes provided by cracks and root holes (Urbanek et al., 2015), although stones in sufficient quantities may also promote infiltration (Urbanek and Shakesby, 2009). Several authors have reported the relevance of preferential flow patterns for water infiltration in hydrophobic soils (DeBano, 2000; Doerr et al., 2000; Buczo et al., 2006). In hydrophobic sandy and sandy loam soils elsewhere, >80% (Ritsema et al., 1997) and 86-99% (Tsukamoto and Ohta, 1988) of water movement has been attributed to preferential flow.

Limited overland flow under antecedent dry settings may be also associated with surface water retention, favoured by vegetation and litter, and micro-topographic concavities on hillslopes. Under these conditions, rainfall may stop before surface depressions had been filled. The longer concentration time required for continuous flow on long hillslopes compared with the duration of the most effective rain showers was considered~~stated~~ by Yair and Raz-Yassif (2004) ~~as~~to be the cause of the low efficiency of runoff processes on slopes.

In wet conditions, particularly in the dense eucalypt plots, it was unclear whether- overland flow (albeit much lower in percentage terms) was promoted by hydrophobicity-linked infiltration-excess ~~and/~~or saturation-excess mechanisms. The persistence of subsurface hydrophobicity, in combination with a thin hydrophilic soil layer, may prevent downward water flux through the soil matrix (Doerr et al., 2000). Any infiltrated water would tend to pond above the hydrophobic layer leading to surface soil moisture build-up and possible saturation (Doerr et al., 2000; Calvo-Cases et al., 2003). Under these conditions, ponded water in the surface saturated layer may be diverted laterally as throughflow unless encountering a vertical preferential flow path, allowing it to reach soil at greater depth and perhaps enter the underlying rock.

During the wettest conditions, overland flow appears to be generated by saturation-excess in the sparse eucalypt and, particularly, oak woodland types, as the soils were hydrophilic rather than hydrophobic. In the sparse eucalypt stand, generation of saturation overland flow may also have been favoured by the greater bulk density and clay content of its soil (Table 1) and its steeper slopes (26-28º), as found elsewhere by Neris et al. (2013). Theoretically ~~S~~saturation overland flow should be~~was~~ greatest in large rainfall events, when water detention by the surface micro-topography is exceeded leading to a greater downhill flux connectivity to develop (Yang et al., 2012). Surface topography may also enhance overland flow connectivity via local rills. Thus it was observed that during this study a rill developed on plot SE3 creating a concentrated surface path for overland flow, which may account for the significantly greater overland flow in that plot compared with in plots SE1 and SE2 (see section 4.4).

In ~~the~~ oak woodland, generation of saturation overland flow may have been favoured by the loamier and also shallower soil than in the eucalypt plantations (Table 1). These will enhance ponding and lead to subsurface lateral flow, which was observed while digging the holes for the overland flow tanks at the O2 and O3 oak plots. No ponding, however, was observed when excavating plot O1, which may be linked to its deeper, and hence less readily saturated soil. This may explain the lower runoff coefficient of plot O1 compared with O2 and O3 (see section 4.4).

Forest management activities can also affect overland flow generation. Under dense eucalypt plantation, plot DE1 had its highest runoff coefficient immediately after clear-felling. Such increases in overland flow and stream peakflow after logging have been widely reported elsewhere, where they have been linked to reduced infiltration capacities due to ground disturbance and soil compaction (Ferreira et al., 2000; Robinson et al., 2003; Eisenbies et al., 2007). In south-central Japan, partial plot thinning (43%) of a Japanese cypress forest led to an increase in runoff coefficient from 33 to 56% (Dung et al., 2012). At the catchment scale, Calder (1993) calculated a runoff increase of 3.3 mm for each percent of an area deforested, based on a world-wide database of hydrologic studies. Nonetheless, some studies have pointed out that such changes in catchment discharge are unlikely to be detected if the area affected ~~constitutes~~ covers less than 20-30% of the total forest cover (Scherer and Pike, 2003; Bathurst et al., 2011).

In *Ribeira dos Covões*, the fact that overland flow after clear-felling was not higher than 2.3% may be due to the thick ground cover of leaves, bark and small branches left in the harvested plot DE1, which would have enhanced water retention capacity and reduced any reduction in infiltration capacity due to splash effects. The enhancement of overland flow in DE1 was quickly reduced, first because of low rainfall in spring and summer and secondly ~~with~~ due to rapid regeneration of vegetation after September 2012, in response to the onset of the rainy late autumn-winter season. The timing of clear-felling may be a determining factor in overland flow impact, since felling performed during spring (rather than in late summer or autumn) allows vegetation to regenerate before autumn rains, minimizing overland flow impacts.

5.2 Implications for catchment streamflow and peri-urban catchment planning

The low overland flow amounts and percentages recorded for all woodland types in *Ribeira dos Covões* over the 2-year period supports the widespread notion of high soil permeability associated with forest vegetation. Nevertheless, different woodland types had distinct effects on overland flow amount and on its temporal pattern. Dense eucalypt plantations provided greater overland flow, mostly produced in dry settings as a result of great severity and resistance of soil hydrophobicity. However, that little overland flow resulted even under extreme soil hydrophobicity highlights the dominance of vertical water fluxes via preferential flow pathways. In oak woodland, and to a lesser extent in the sparse eucalypt stand, overland flow is mostly produced in prolonged rainfall events during wet weather conditions.

~~The overland flow measurements undertaken in this study were conducted at a plot scale.~~ Overland flow responses, however, tend to diminish with increasing contributing area (van de Giesen et al., 2000, 2005; Ferreira et al., 2011; Chamizo et al., 2012). Based on measurements of soil hydrological properties at point-scale, Ferreira et al. (2015) suggested that woodland areas in *Ribeira dos Covões* could be an important source of overland flow in storm events during and immediately following~~during~~ the summer dry season~~s~~ and other prolonged dry periods-. ~~Nevertheless,~~ The very low runoff coefficients of the current plot-scale results in the same catchment ~~regarding to the same study site showed very low runoff coefficients.~~ ~~This T~~demonstrates that the inverse relationship between overland flow and contributing area~~decline~~ can be marked even with relatively small changes in area. This tallies with the findings of~~For example,~~ van de Giesen et al. (2005), who recorded a decrease of 40–75% in overland flow from short (1.25 m) to long plots (12 m). On the other hand, Mounirou et al. (2012) reported similar runoff amounts from 50 and 150 m^2 plots, though both were significantly lower than the smallest plot (1 m^2) used. In an experimental study, Chamizo et al. (2012) found an optimal plot length of 20 m to determine runoff and sediment export rates representative of a catchment. At a much larger spatial scale, Cerdan et al. (2004)~~, in turn, observed~~ recorded a strong decrease in mean runoff coefficients with increasing area in studies performed at larger scales: three times lower for 90 ha than 450 m^2, and ten times for 1100 ha than 90 ha.

Decreasing overland flow with increasing slope length is usually explained with greater opportunity for water infiltration on long than on short slopes (van de Giesen et al., 2005). It has also been attributed to increased soil heterogeneity with area, in terms of greater spatial variability in soil infiltration capacity (Cerdan et al., 2004; Mounirou et al., 2012), wettable patches and macropores, which can act as sinks for water (Calvo-Cases et al., 2003; Güntner and Bronstert, 2004; Nasta et al., 2009), as well as the temporal dynamics of the rainfall–runoff events (van de Giesen et al., 2005). Some authors have argued that spatial variability only has a scale-related effect on total runoff during relatively short rainfall events (van de Giesen et al., 2005; Mounirou et al., 2012). In *Ribeira dos Covões*, considering the small amounts of overland flow generated under woodland land-use even for relatively small runoff plots, it can be concluded that the generation in woodland areas of sufficiently continuous overland flow able to reach valley floors and channels would be rare. It would also suggest that patches of all three types of woodland could act as sinks for overland flow generated on upslope impervious urban surfaces.

~~Although the minor overland flow measured in the study catchment supports the protective role of forest land-use during storm events,~~ The question remains, however, about overland flow responses in rainfall events more extreme than those recorded in the two-year study. ~~t~~The highest daily rainfall recorded in the monitoring period was only 48 mm, which is less than a 2-year return period event (Brandão et al., 2001). On 25th October 2006, however, ~~hourly and~~following a period of very wet antecedent weather, a daily rainfall of 102 mm was recorded at Bencanta-Coimbra with a maximum hourly intensity of~~reached~~ 56~~5~~ mm ~~and 102 mm, respectively,~~ leading to major flooding of the *Ribeira dos Cov~~o~~ões*. According to Brandão et al. (2001), daily rainfall events of 94 mm and 112 mm at Coimbra have return periods of 10- and 50-years, respectively. ~~Since t~~The contribution from woodland areas to the 2006 flood is unknown and~~, O~~o~~verland flow responses in more extreme events~~ can only be surmised. As the 25th October rainstorm followed a prolonged period of wet weather, it is highly likely that even in the dense eucalyptus the soil would have been largely hydrophilic and any overland flow generated in all three woodland types would probably have been saturation-excess in type.- It is clearly possible that in such an extreme event~~s~~ the percentage saturation overland flow generated from all three woodland areas would have ~~ill~~ been much greater than the maxima of <3-% recorded in the current study. Also a greater proportion ~~and will also more readily be~~ would have been transferred to downslope areas, since surface water retention capacities provided by litter and micro-topographic concavities would have~~ill~~ been exceeded. ~~Thus, s~~~~S~~Although some studies have emphasized the limited storage capacity of forested terrain during larger storms and its minor role in flood protection (Bathurst et al., 2011; Eisenbies et al., 2007), it is considered that the high infiltration capacities of the soils of the catchment when hydrophilic (Ferreira et al., 2015) and the high storage capacities of the comparatively deep (>3m) sandstone soils of the dense and sparse eucalyptus sites would have limited the overland flow contribution from the eucalyptus woodland areas and retained some sink role for urban runoff, with really high percentages of overland flow restricted to the oak woodland areas with their shallow, easily saturated soils. It is arguable, however, that the overland flow contribution from the dense eucalypt areas would have been much higher if an extreme storm of the magnitude of the 25th October 2006 event had occurred after dry antecedent weather when the dense eucalyptus soil would have been highly hydrophobic rather than hydrophilic. Clearly the timing of extreme events in relation to woodland -and soil types in a peri-urban catchment is of crucial significance to the size of overland flow responses and degree of downstream flooding.

~~Based on overland flow differences between woodland types, it could be possible that dense eucalypt plantations provide some overland flow contribution into downslope areas under extreme storms recorded immediately after the summer. The potential contribution of dense eucalypt stands into flash floods, is supported by the greatest infiltration-excess overland flow measured at plot scale, as a result of greatest severity and spatial extent of hydrophobicity. On the other hand, if extreme storms are recorded during wet seasons, sparse eucalypt stands and particularly oak woodland, could be more prone to contribute into large-scale floods, since overland flow in those forest types is typically produced by saturation-excess mechanisms, according with plot results.~~

~~Based o~~~~In *Ribeira dos Covões* results, although the influence of woodland areas on catchment streamflow is unknown, based on plot-scale results it is possible it is arguable that dense eucalypt plantations could provide some would be most likely to contributeion to flash floods during extreme storms that occur immediately after the summer, due to infiltration-excess overland flow favoured by its greater severity and spatial extent of~~

~~hydrophobicity. On the other hand, sparse eucalypt stands and particularly oak woodland, may have some influence on would contribute to large-scale floods following wet antecedent weather, since overland flow in those forest types is typically produced by saturation-excess mechanisms.~~

~~On 25th October 2006, a rainfall event at Coimbra-Bencanta of 102 mm after a long dry summer, led to a flash flood in *Ribeira dos Covões* catchment. According to Brandão et al. (2001), daily rainfall events of 94 mm and 112 mm at Coimbra have return periods of 10- and 50-years, respectively. Although the contribution from woodland areas to this flood is unknown, based on overland flow measurements performed under local woodland, dense eucalypt plantations could have some contribution to this flood, whereas sparse eucalypt and oak sites could provide upstream overland flow sinks.~~

The hydrological responses~~role~~ of different woodland types in extreme events, ~~on flood events,~~ however, clearly needs further investigation. Additional plot monitoring in *Ribeira dos Covões* ~~would be~~ is needed to cover overland flow responses in larger storm events than occurred in the study period after dry and wet antecedent conditions if more reliable inferences concerning the influence of woodland types within peri-urban mosaics on flood risk are to be drawn. ~~.and improve understanding of the role of woodland on overland flow under these conditions. Furthermore, the impact of woodland types on overland flow should also be performed at a larger scale, in order to understand its influence on catchment scale. In *Ribeira dos Covões*, streamflow measurements have been carried out to assess the role of woodland areas at the sub-catchment scale. This information would be particularly important for mixed land-use catchments.~~

Woodland is the dominant land-use in *Ribeira dos Covões* catchment, followed by urban surfaces, which in some places interrupts woodland patches (Figure 1). The increase in impervious area and catchment discharge with ~~U~~additional urbanization in recent years ~~seems to have promoted increased catchment discharge, and this is~~is expected to continue given~~in view of the character of~~ the future urban development already approved (Ferreira et al., 2013). ~~Considering t~~The small amounts of overland flow generated in all three ~~local~~ woodland types demonstrates that patches of woodland~~, this land-use~~ can provide potential ~~overland flow~~ sinks for overland flow generated ~~such flow emanating~~ from upslope impervious~~meable~~ urban surfaces~~areas~~ if they naturally or are directed to flow into such patches. ~~A discontinuous pattern of urban and woodland land-uses can interrupt flow connectivity over the landscape and minimize the detrimental hydrological impacts of urbanization (Ferreira et al., 2015). However, increasing woodland fragmentation driven by urbanization will reduce downslope opportunities for water infiltration and retention, which may enhance the generation of continuous overland flow and exacerbate urbanization impacts on catchment streamflow and increasing flood hazard.~~ The magnitude and effectiveness of such a sink role in a peri-urban catchment, ~~se impacts, however,~~ will be ~~ould be~~ affected (1) by the type of woodland, given the ~~associated~~ differences in overland flow mechanisms and responses shown by this study, (2) their distribution within the catchment in relation to upslope urban surfaces and (3) the extent to which upslope urban runoff flows into them. It is argued here that

~~K~~knowledge of the impact of woodland areas, and particularly of woodland type on temporal overland flow dynamics should be taken into consideration in integrated planning and management of catchments undergoing urban development, particularly as regards planning the type and distribution of woodland patches and the delivery of urban surface runoff into these patches. Further investigation should be carried out in order to improve understanding of the appropriate sizes and locations of distinct woodland areas within peri-urban catchments, in order to minimize the hydrologic impacts of urbanization and protect downslope urban cores from flood hazard.

6 Conclusions

In the peri-urban catchment of *Ribeira dos Covões* in central Portugal, —three distinct woodland types on sandstone and limestone produced overland flow representing less than 3% of the incident rainfall, based on measurements performed on small (16 m^2) plots over 2--years of monitoring. Plots on a managed dense eucalypt stand generated significantly 2.5 times more~~higher~~ overland flow than plots on sparse eucalypt or oak woodland on abandoned peri-urban land.~~, which differed only slightly.~~ ~~Although the underlying bedrock can also influence hydrological processes, woodland type appears to be far more important, given the differences in soil hydrological properties and overland flow generation recorded on dense and sparse eucalypt stands, as they are both located on sandstone.~~

In dry conditions, hydrophobicity-linked infiltration-excess overland flow was the dominant means of downslope water movement. This process was particularly important in dense eucalypt plantations, where hydrophobicity was more extreme, spatially contiguous and resistant to breakdown with rainfall than was the case in the other two woodland types. Under hydrophobic conditions at the dense eucalyptus sites, overland flow amount strongly increased with rainfall amount and intensity, but median and individual plot overland flow coefficients attained maxima of~~ did not exceed~~ 2.2% and 2.7%, respectively. In contrast, in the sparse eucalypt plots, their moderate hydrophobicity after dry periods was easily broken down, and percentage overland flow was greatest (albeit ≤0.5%) in smaller rainfall events ~~(overland flow coefficient ≤<0.5%),~~ when the soil failed to become~~was not rendered~~ wettable within the event. The weak hydrophobic properties observed in oak woodland plots led to a maximum overland flow coefficient of only 0.4% in storms following dry antecedent weather, and median plot values of 0.3% for storms during the dry season.

In periods of wet weather, however, saturation overland flow occurred most readily in oak woodland followed by sparse eucalypt stands. Relatively high soil moisture contents maintained throughout wet periods enhanced saturation overland flow~~ by saturation~~, so that plot runoff coefficients reached 1.~~2~~7% and 2.2% on the sparse eucalypt and oak woodland ~~plots~~sites, respectively. ~~On~~ At the latter, saturation was favoured by the shallow soil overlying limestone, its loamy texture and subsurface lateral flow, whereas in the sparse eucalypt stand, saturation was favoured by the high bulk density and clayey nature of the soil. In both woodland types, overland flow strongly increased with rainfall amount and soil moisture. In contrast, in the dense eucalypt plantation, median overland flow ~~never did not~~ never exceeded 1.0% of rainfall in periods of wet weather.

Interception by the different woodland types was not significantly different, based on exploratory throughfall measurements performed. It is thought to have been important in reducing overland flow responses only during small rainfall events following antecedent dry weather, as throughfall was high (and interception was low) in percentage terms during large events and wet periods due to canopy saturation. In addition, surface roughness, associated with the litter layer promoted water retention and decreased lateral flow connectivity.

Important implications of this study for managing peri-urban catchments are that patches of semi-natural and managed woodland are critical in order to retain rainfall, promote infiltration and act as sinks for overland flow from upslope. In fully urbanized catchments, the lack of rainfall interception and the size, and often contiguity, of areas covered by impermeable surfaces tend to promote rapid overland flow and the possibility of flooding. Authorities concerned with catchment management and urban planning, therefore, should try to incorporate woodland patches in any development proposal not only ~~in order~~ to reduce the total runoff-generating area, but also to ~~and~~ provide sinks for runoff produced on impermeable urban surfaces upslope. Thus, the most satisfactory compromise is likely to be a mosaic of diverse land-uses designed to disrupt overland flow connectivity. Nevertheless, the varying impact of different woodland types on overland flow processes and catchment hydrological response should also be considered. Identifying the best arrangement of such patches (e.g. type of woodland, extension and location within the landscape) while maximizing the use of land for urban development should now be a research priority. A second research need is for field data on overland flow responses within this mosaic in more extreme, potentially flood-producing rainstorms than occurred within the 2-year monitoring period of this study.

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Table 2 – Spearman rank correlation coefficients between rainfall, throughfall, overland flow and soil properties (* and ** represent cor
with 0.05 and 0.01 levels of significance; n=511).

	Throughfall (mm)	Hydrophobicity 0-2cm	 2-5cm	 5-10cm	Soil moisture (%)	Overland flow (mm)
Rainfall ~~amount~~(mm)	0.83**	-0.31**	-0.29**	-0.30**	0.25**	0.51**
I_{30} (mm h^{-1})	0.57**	-0.13**	-0.10*	-0.09*	-0.01	0.51**
Throughfall (mm)	-	-0.20**	-0.22**	-0.16**	0.20**	0.45**
Hydrophobicity						
0-2cm	-0.20**	-	0.68**	0.42**	-0.51**	-0.03
2-5cm	-0.22**	0.68**	-	0.72**	-0.52**	-0.05
5-10cm	-0.16**	0.42**	0.72**	-	-0.42**	0.04
Soil moisture (%)	0.20**	-0.51**	-0.52**	-0.42**	-	-0.01
Soil texture						
Sand (%)	-	0.25**	0.28**	0.28**	-0.19**	0.25**
Silt (%)	-	-0.26**	-0.30**	-0.36**	-0.20**	-0.23**
Clay (%)	-	-0.15**	-0.18**	-0.23**	-0.09*	-0.23**
Organic matter (%)	-	0.14**	0.16**	0.22**	0.04	0.15**
Bulk density (g cm^{-3})	-	-0.06	-0.05	-0.07	-0.21**	-0.12**

Slope (°)	0.09	0.07	0.014**	0.13*	-0.32**	0.02

Differences in overland flow, hydrophobicity and soil moisture dynamics between Mediterranean woodland types in a peri-urban catchment in Portugal

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Abstract

Forest hydrology has been widely investigated, but the impacts of different woodland types on hydrological processes within a peri-urban catchment mosaic are poorly understood. This paper investigates overland flow generation processes in three different types of woodland in a small (6.2 km^2) catchment in central Portugal that has undergone strong urban development over the past 50 years. A semi-natural oak stand and a sparse eucalyptus stand on partly abandoned peri-urban land and a dense eucalyptus plantation were each instrumented with three 16 m^2 runoff plots and 15 throughfall gauges, which were monitored at c. 1- to 2-week intervals over two hydrological years. In addition, surface moisture content (0-5cm) and hydrophobicity (0-2cm, 2-5cm and 5-10cm) were measured at the same time as overland flow and throughfall. Although all three woodland types produced relatively little overland flow (< 3% of the incident rainfall overall), the dense eucalypt stand produced twice as much overland flow as the sparse eucalypt and oak woodland types. This contrast in overland flow can be attributed to infiltration-excess processes operating in storms following dry antecedent weather when severe hydrophobicity was widespread in the dense eucalypt plantation, whereas it was of moderate and low severity and less widespread in the sparse eucalypt and oak woodlands, respectively. In contrast, under wet conditions greater (albeit still small) percentages of overland flow were produced in oak woodland than in the two eucalypt plantations; this was probably linked to saturation-excess overland flow being generated more readily at the oak site as a result of its shallower soil. Differences in water retention in surface depressions affected overland flow generation and downslope flow transport. Implications of the seasonal differentials in overland flow generation between the three distinct woodland types for the hydrological response of peri-urban catchments are addressed.

Keywords: Eucalypt plantations, oak woodland, saturation-excess overland flow, infiltration-excess overland flow, hydrophobicity, soil moisture content.

1. Introduction

Forest covers 31% of the world's land surface (FAO, 2010) and 35% of mainland Portugal (ICNF, 2013). Globally forest cover has increased in recent decades as a result of greater demand for timber and environmental concerns (e.g. Robinson et al., 2003). However, in peri-urban catchments located in previously forested terrain, forest cover has decreased where urbanization has led to progressive deforestation and forest fragmentation (Nowak, 2006) and remaining woodland can often change in character because of altered or abandoned management.

Forest hydrology has been widely documented, particularly with respect to some hydrological processes. Interception has been measured and modelled for many forest stands, indicating differences linked to distinct canopy architectures and woody matter and leaf characteristics and biomass (Muzylo et al., 2009; Rao et al., 2011). As a result of these factors (and climatic factors, notably rainstorm size distribution), throughfall varies greatly between forests, typically from 65 to90% of precipitation, with stemflow generally varying from zero to 15 % (Herwitz and Levia, 1997; Crockford and Richardson, 2000; Wei et al., 2005). Differences in these processes can affect soil moisture distribution (Savva et al., 2013; He et al., 2014) and overland flow generation. Partly because overland flow is often considered a minor component of forest hydrology (Eisenbies et al., 2007; Gomi et al., 2008), few studies have focused on differences in overland flow between different forest types, and in particular between unmanaged, often abandoned woodland types affected by peri-urbanization process and pre-existing managed forest plantations.

Hydrophobicity, induced by substances (especially some resins and waxes) produced by some vegetation species (Dekker and Ritsema, 1994), has become increasingly recognized as an important soil property that can affect overland flow in forest soils, particularly in seasonally dry environments. Thus in a eucalypt plantation area of north-central Portugal, temporal changes in hydrophobicity were found to explain 74% of overland flow variation (Ferreira et al., 2000). Many studies have demonstrated differences in degrees of hydrophobicity between different vegetation types (e.g. DeBano, 2000; Zavala et al., 2009; Lozano et al., 2013). Eucalypt stands are renowned for inducing high levels of hydrophobicity (Doerr et al., 1996; Ferreira et al., 2000; Santos et al., 2013), with some studies in Portugal linking greater overland flow produced under eucalypt than pine plantations with enhanced soil hydrophobicity under eucalyptus (Ferreira et al., 2000; Keizer et al., 2005). In contrast, little is known about overland flow in Mediterranean oak stands. This is important as differences in overland flow between distinct forest stands can contribute to variations in total streamflow and the stormflow component with forest land-use change (Fritsch, 1993; Grip et al., 2005), whereas in many cases streamflow differences in areas subject to forest species change are attributed to evapotranspiration adjustments (e.g. Swank and Douglass, 1974; Otero et al., 1994).

Although it is widely accepted that forests regulate water yield and reduce the size of most streamflow responses to rainfall because the high permeability of their soils (Eisenbies et al., 2007; Bathurst et al., 2011), the role of forest areas in flood protection in extreme rainfall events has been hotly debated. Some have argued that interception and higher soil moisture deficits (of deeper, more porous and drier soils) under forest should reduce floods by removing a proportion of the storm rainfall (e.g. Bathurst et al., 2011), whereas others have argued that such water retention by forest is minimal in the extreme rainfall events that are responsible for floods (Eisenbies et al., 2007; Hümann et al, 2011; Komatsu et al., 2011),

Impacts of different forest and woodland stands on overland flow may be particularly important in the hydrology of small peri-urban catchments, as they are often characterized by a mosaic of different urban and non-urban land-uses, including woodland types on areas of altered or abandoned forest or agricultural management, as well as patches of pre-existing managed forest. Theoretically in such catchments, patches of forest types with permeable soil can break flow connectivity over the landscape and act as sinks to overland flow from upslope urban surfaces, whereas any overland flow generated on forest types with soils of lower permeability may reach downslope urban surfaces and represent an additional contribution to the urban flood hazard. Such peri-urban situations, particularly in areas of Mediterranean climate, have been little studied (Ferreira et al., 2015).

This paper investigates the influence of three different types of woodland occurring within a peri-urban mosaic on overland flow generation in the *Ribeira dos Covões* catchment in an area of Mediterranean climate in central Portugal. Two of the woodland types investigated ((i) sparse eucalyptus adjacent to eucalyptus plantations and (ii) oak woodland) have been strongly influenced by semi-abandonment of land with peri-urbanization, whereas the third comprises pre-existing managed dense eucalyptus. A previous investigation in the same catchment (Ferreira et al. (2015)assessed temporal changes in soil properties (soil matrix infiltration capacity, soil moisture content and hydrophobicity at a network of points in different landscape units found in the catchment (woodland-sandstone, woodland-limestone, agriculture-sandstone, agriculture-limestone, urban-sandstone and urban-limestone); it then discussed their potential impacts on overland flow within the catchment. Results suggested that woodland areas might provide important sinks of overland flow during wet periods due to the high infiltration capacities recorded on their soils, but might act as overland flow sources in storms following dry periods (especially in summer) because of the hydrophobic nature of the soil matrix. The current paper tests these tentative suggestions of the previous paper by using a plot-scale monitoring approach to assess temporal differences in overland flow generation, and its influencing factors, between the sparse eucalyptus, oak woodland and managed dense eucalyptus woodland types over a two-year period. The focus is on the roles played by differing temporal regimes in hydrophobicity and soil moisture of the three woodland types studied. The implications of the results for planning land-use mosaics in peri-urban catchments in such environments are also explored.

2. Study area

The study was carried out in the peri-urban *Ribeira dos Covões* catchment (8º27´W, 40º13´N), located 3km NW of Coimbra, the largest city in central Portugal. The catchment (Figure 1) is 6.2km^2 in area, is aligned S-N and ranges in altitude from 34 to 205 m a.s.l. The area has a Mediterranean climate, with a mean annual temperature of 15°C and an average annual rainfall of 892 mm over the period 1941-2000 recorded at Coimbra-Bencanta (national meteorological weather station 12G/02UG), sited 0.5 km north of the study catchment. A dry and hot season occurs from June to August (8% of annual rainfall), whereas the rainiest period is from November to March (61% of annual rainfall). Rainfall events are mostly small, with 83% of daily rainfalls in 2001-13 at Coimbra-Bencanta being <10 mm. Annual maximum daily rainfalls in 2001-13 ranged from 20 mm to 102 mm. The catchment is underlain by sandstone (57%) and limestone (43%). Soils developed on sandstone are classified as Fluvisols and Podsols, following the WRB (2006) classification, and are generally deep (>3 m), while the Leptic Cambisols found on limestone slopes are typically shallow (<0.4 m) (Pato, 2007).

The catchment has undergone profound land-use changes over the last five decades, mainly associated with urbanization and planting of eucalyptus for timber production. Between 1958 and 2007, the urban area expanded from 6% to 32% and woodland expanded from 44% to 64%, at the expense of a marked decrease in agricultural land from 48 to 4%. Since 2007, further urbanization has occurred mainly through deforestation. Thus by 2012, the urban area had increased to 40%, while the increasingly fragmented woodland area had decreased to 53% (Figure 1).

Currently, the woodland area consists mainly of *Eucalyptus globulus* Labill. plantations (55%), but with some mixed stands of eucalypt and pine (29%), scrubland (15%) and relict oak woodland composed of *Quercus robur L.*, *Q. faginea broteroi* and *Q. suber L.* trees (1%) (Figure 1). Generally, eucalypt plantations occur on sandstone, but some areas, abandoned following logging, are now covered by sparse eucalypt stands with a dense scrub understorey. On limestone, vegetated areas are largely covered by shrubs (e.g. *Pistacia lentiscus*, *Spartium juncium*, *Cistus crispus*, *Ulex jussiaei*), but with semi-natural oak stands. In the oak area, a number of stone walls have survived from an earlier agricultural land-use, mainly olive plantations. Thus both the sparse eucalyptus and oak woodland types have been strongly influenced by semi-abandonment of land with peri-urbanization.

3. Methodology

3.1 Experimental design and measurements

Three runoff plots were established in each of the three principal types of woodland within the *Ribeira dos Covões* catchment (Figure 1): (1) dense eucalypt plantation, which contains occasional pine and acacia trees (plots DE1, DE2 and DE3); (2) sparse eucalypt areas, with an extensive cover of scrub (SE1, SE2 and SE3); and (3) oak woodland (O1, O2 and O3). The spatial distribution of woodland types within the catchment and site accessibility led to topographic and lithological (and hence soil) differences between the three study sites (Table 1). Eucalypt plantations, as they overlie sandstone, exhibit a sandy-loam soil in dense plantations, but a loamy sand soil in sparse stands, whereas the oak woodland is located on limestone and has a loamy soil.

The three runoff plots at each study location were placed 20 – 500 m apart, depending on local constraints (e.g. avoiding close proximity to tracks and locations with extensive stone lag). The plots were 8m long by 2m wide and were bounded by 15cm high metal strips (inserted into the soil to a depth of 5-10cm).Each plot was connected to a modified Gerlach trough to collect eroded sediment and thence to a tipping-bucket device and a 50-litre tank for recording and collecting the overland flow. Plot installation was completed on 10th

January 2011, but data collection started one month later, in order for the plots to recover from any disturbance caused during installation.

Each plot was further equipped with five manual throughfall gauges to give an approximate idea of differences between woodland types. The throughfall gauges comprised funnels (20 cm in diameter) connected to a storage bottle (3-litre capacity), installed at the soil surface within half-buried PVC pipes (20 cm in diameter and 30 cm long). The five gauges were placed randomly 0.5-2m outside the plot boundaries beneath the tree and/or scrub vegetation. Rainfall data were based on weighted-average results of five tipping-bucket rain gauges installed in open areas within and near the catchment (Figure 1). Given the relatively small number of throughfall gauges, throughfall measurements only represent exploratory data to give a comparison between woodland types; water inputs to the plots were based on rainfall data.

Hydrophobicity and soil moisture content were measured on undisturbed land adjacent to each plot. Soil hydrophobicity was assessed at 0-2 cm, 2-5 cm and 5-7 cm depths along two 1-m transects at either side of each plot using the ‘Molarity of an Ethanol Droplet test’ (Doerr, 1998). Sets of fifteen droplets of increasing ethanol concentration were applied along each transect until infiltration of at least eight droplets of the same concentration occurred within 5 seconds. The results for each transect were classified according to the following five repellency ratings and associated ethanol concentrations: wettable (0%); low (1, 3 and 5%); moderate (8.5 and 13%); severe (18 and 24 %); and extreme (36 and >36 %) hydrophobicity. Gravimetric soil moisture content was determined in the laboratory by oven-drying at 105ºC for 24h. On each measurement occasion, this was done using one composite soil sample per plot (0-5cm soil depth), which was obtained by mixing 10 samples collected randomly on undisturbed land around each plot. Gravimetric was converted into volumetric water content using the mean soil bulk density of each site, calculated from 11 random soil samples of 143 cm^3 volume collected near to each plot, using purpose-built soil ring samplers of 5 cm diameter and 7.3 cm length.

Overland flow, throughfall, hydrophobicity and soil moisture were measured on 61 occasions at 1- to 2-week intervals (depending on previous rainfall) over the 2-years from 9th February 2011 to 14th April 2013. In March 2012, part of the dense eucalypt site was clear-felled, destroying plot DE2 (where monitoring was abandoned) and affecting tree interception at plot DE1. Owing to vandalism and theft of equipment on several occasions after clear-felling, throughfall measurement at the dense eucalypt plot locations was also abandoned from mid-2012 onwards.

3.2 Data analysis

In view of the non-normal distribution of the overland flow, throughfall, soil moisture and hydrophobicity data, non-parametric statistical tests were used to assess differences in median values between the three woodland types and between plots of the same woodland type. The Kruskal–Wallis test was employed to test the significance ($p<0.05$) of the differences with woodland type in overland flow, throughfall, hydrophobicity and soil moisture, and their seasonal variations. The statistical significance of differences in medians between seasons/plots/stands was assessed using the Least Significant Difference (LSD) test. The Spearman correlation coefficient (*r*) was used to assess whether significant associations ($p<0.05$ and $p<0.01$) existed between rainfall characteristics (1- to 2-weekly totals, maximum 30-min rainfall intensities (I_{30}) and 30-day antecedent rainfall) and soil hydrological properties (hydrophobicity and soil moisture), as well as overland flow. All statistical analyses were carried out using IBM SPSS Statistics 22 software.

4. Results and Analysis

4.1 Rainfall

Overall, rainfall over the 2-year monitoring period (totalling 1581.7 mm) was relatively low, with annual rainfalls in 2011 and 2012 being 18 and 38% respectively below the long-term (1941-2000) average of 892 mm. The 61 measurement periods differed markedly in total rainfall amount (1.8-113 mm) (Figure 2), number of rainfall days (2-12) and maximum 30-min rainfall intensity (I_{30}: 0.6-24.8 mm h^{-1}), but none represented extreme rainfall events (all beneath 2-years Intensity-Duration-Frequency curves for Coimbra (Brandão et al., 2001). The seasonal pattern was typically Mediterranean, with distinctly lower rainfall in summer (4% of total rainfall fell in June to August) compared with 35% in autumn, 32% in winter and 28% in spring. Nevertheless, there was also a very dry period in winter 2011/12 from 21st December 2011 to 20th March 2012 (37 mm). In contrast, November 2011, January 2013 and March 2013 were wetter than the long-term 1941-2000 averages (163 vs 111 mm, 166 vs 116 mm and 228 vs 87 mm, respectively). In total there were 333 days with rain during the 2-year monitoring period, with 47 daily falls exceeding 10.0 mm, of which four exceeded 25.0 mm. The highest daily falls were 48.1 mm on 14th December 2012, 43.1 mm on 7th March 2013, 29.0 mm on 19th January 2013 and 26.8 mm on 2nd November 2011. These falls are well below 102 mm fall recorded on 25th October 2006, which led to floods within the catchment.

4.2 Throughfall

Although, given the small number of gauges, assessments were only exploratory, throughfall for the period 2nd April 2011 to 5th March 2012 (periods 3-23), when measurements were carried out at all three woodland sites, was higher in dense eucalypt (92% of rainfall) than in sparse eucalypt (87%) and oak stands (82%) (Figure 2). For the 2-year period 2nd April 2011 to 14th April 2013 (periods 3-61), however, overall throughfall percentages were rather higher (97% and 92% of rainfall in the sparse eucalypt and oak stands respectively. In both periods, differences in percentage throughfall between woodland types were found to be not statistically significant ($p>0.05$).

Throughfall percentages increased significantly with rainfall amount and maximum intensity (r=0.83 and 0.57, respectively; $p<0.01$). Generally throughfall percentages for measurement periods were lower in summer than winter, with median values of 90%, 74% and 46% in summer, and 93%, 92% and 86% in winter, for dense eucalypt, sparse eucalypt and oak stands, respectively. No throughfall was recorded for rainstorms of less than 3.7 mm following antecedent dry weather (e.g. periods 10 and 34).

4.2 Hydrophobicity

In all soil layers, hydrophobicity was most severe and frequent in the dense eucalypt plantations, intermediate in the sparse eucalypt stand and least in the oak woodland ($p<0.05$) (Figure 3). In the oak stand, hydrophobicity was absent on many measurement dates (69% of occasions at both 0-2 cm and 2-5 cm and 48% of occasions at 5-7 cm) and was largely of low or moderate severity when present. In this woodland type, hydrophobicity was mainly transient in nature, being recorded in all the sampling sites only on 14%, 13% and 17% of monitoring occasions, at 0-2 cm, 2-5 cm and 5-7 cm depth, respectively. In the sparse eucalypt site, hydrophobicity showed the greatest spatial and temporal variation; hydrophilic conditions were dominant on 49%, 34% and 39% of the measurement dates, at 0-2 cm, 2-5 cm and 5-7 cm, respectively, but hydrophobicity was mostly moderate to severe when present. As in oak woodland, the sparse eucalypt stand showed a transient and patchy hydrophobic pattern, with widespread hydrophobicity recorded on just 26% of the 61 measurement occasions at 0-2 cm and 5-7 cm and on 24% of occasions at 2-5 cm depth. In contrast, in dense eucalypt plantations, hydrophilic conditions were only observed on 41%, 15% and 13% of occasions, at 0-2 cm, 2-5 cm and 5-7 cm depth respectively, with severe to extreme hydrophobic properties being dominant and widespread on 53%, 55% and 70% respectively of occasions when hydrophobicity was present.

Hydrophobicity showed the same marked seasonal pattern at all three study sites. It was typically absent during late autumn and winter, and most severe and widespread during summer. After dry periods, hydrophobicity was more resistant to being broken down during rainfall events in eucalypt plantations and disappeared earlier in oak woodland. Also, hydrophobicity was re-established more quickly in dry periods under eucalypt than under oak. Thus after the largest rainfalls in autumn 2011 and beginning of winter 2012, hydrophobicity required five months longer to reappear in oak than in the eucalypt stands.

In dense eucalypt stands, hydrophobicity increased in frequency and severity with soil depth (differences between 0-2 cm and 5-10 cm layers, $p<0.05$). Also, more rainstorms were required to reduce hydrophobicity levels in deeper soil. Extreme hydrophobicity was recorded on 18%, 13% and 30% of occasions respectively at 0-2 cm, 2-5 cm and 5-10 cm. A similar pattern with depth occurred at the sparse eucalypt site, despite lower hydrophobicity severity and coverage (extreme hydrophobicity was recorded on 8%, 13% and 15% of occasions, at 0-2 cm, 2-5 cm and 5-10 cm depth, respectively). In contrast to eucalypt sites, hydrophobicity did not vary significantly with soil depth in oak woodland ($p>0.05$), although it showed a tendency to decrease in severity but increase in temporal frequency with soil depth (Figure 3).

Although hydrophobicity severity and spatial frequency varied with antecedent weather at all sites and at all depths in all woodland types, inverse relationships with storm rainfall and throughfall amount, although statistically significant ($p<0.01$), are weak (r never exceeding -0.31) and are not statistically significant in the case of maximum rainfall intensity ($p>0.05$) (Table 2).

4.3 Soil moisture content

Median surface soil moisture content (0-5 cm depth) over the two-year period was similar in dense (15%) and sparse (18%) eucalypt stands ($p>0.05$), but significantly higher at oak sites (29%) ($p<0.05$) (Figure 4).

Soil moisture content increased significantly with preceding period rainfall amount and throughfall ($p<0.01$), although relationships were not very strong (Table 2). It was substantially lower in summer than in other seasons ($p<0.05$), with a similar median value (8%) for all woodland types. Soil moisture was much higher in autumn, winter and spring (24%, 25% and 21%, respectively), but with variations between years. During spring, median soil moisture content was higher in 2013 (22%) than in both 2011 (16%) and 2012 (11%) ($p<0.05$). In autumn, soil moisture was significantly higher in 2011 than in 2012 (28% vs 17%) ($p<0.05$). In winter, median soil moisture reached highest values in 2013 (26% compared with 19% in 2011 and 20% in 2012). Generally, higher soil moisture content was observed during autumn 2011 (median values of 27%, 33% and 27% for ED, EO and O, respectively), winter 2013 (median values of 23%, 24% and 36% for ED, EO and O, respectively) and spring 2013 (median values of 18%, 22% and 36% for ED, EO and O, respectively). Soil moisture content reached highest values of 37%, 32% and 49% in ED, EO and O in winter 2013, but the peak value of 47% in the EO site was attained in autumn 2011.

Generally, soil moisture content showed strong and statistically significant inverse correlations with hydrophobicity (r ranged between -0.42 and -0.52 for different soil depths, $p<0.01$, Table 2). It was also significantly affected by soil properties, such as particle size distribution and bulk density, as well as slope gradient, although correlations coefficients were rather low (Table 2).

4.4 Overland flow

The median plot values of overland flow amount in mm (above) and as a percentage of rainfall (below) for each woodland type in each of the 61 measurement periods is shown in Figure 5. Although overland flow was generated in most measurement periods (97, 92 and 89% of occasions for dense eucalypt, sparse eucalypt and oak stands, respectively), median overland flow exceeded 1% of period rainfall on just 8, 4 and 3 occasions out of 61 for dense eucalypt, sparse eucalypt and oak sites, respectively, and never exceeded 3% (Figure

5). Overland flow amounts (median values for individual periods), were significantly higher in the dense eucalypt plantation than in the sparse eucalypt and oak stands ($p<0.05$, Kruskal-Wallis and LSD tests) and overland flow over the two-year period was over twice as high in dense eucalyptus (6.9 mm, 0.43%) than at the sparse eucalyptus (2.6 mm, 0.16%) and oak woodland (2.9 mm, 0.18%) plots. Differences in the temporal pattern of overland flow were also observed between woodland stands. Dense eucalypt plantation plots generated greater percentage overland flow (medians of up to 2.2%) in rainstorms occurring after dry antecedent weather (especially in late spring, summer and at the beginning of autumn), whereas in wet conditions, even in large events, it never exceeded 1.0 %. In the sparse eucalypt stand, median overland flow varied in contrary fashion over the year, with higher values in wet weather of autumn, winter and spring and lower values in storms following dry periods, particular in summer and early autumn. Thus the maximum recorded median runoff coefficient was only 0.4% in a measurement period after dry weather but 1.3% after wet weather. In the dense eucalypt plantation, the highest percentage overland flow values were recorded in moderate rainfall events (4-23 mm and I_{30}= 3-16 mm h^{-1}), whereas in the sparse eucalypt stand highest percentage overland flow occurred in relatively small rainfall events (4-10 mm and I_{30}=3-6 mm h^{-1}). Again, in contrast to the dense eucalypt plots, in oak woodland overland flow was mainly produced after the wettest antecedent weather and soil moisture conditions, attaining higher values mostly in larger rainfall events (>10 mm) in winter and spring 2013, the wettest part of the 2-year study. In the oak woodland, however, even in the wettest periods, median runoff coefficient values of the three replicated plots never exceeded 0.6% and following dry weather both median and individual plot runoff coefficients never exceeded 0.4%.

Under dense eucalypt plantation, overland flow varied little between runoff plots, except immediately after clear-felling at one of the plots. Thus, the clear-felled plot (DE1) experienced its highest runoff coefficient (2.3%) immediately after logging in late winter (period 22), but it was quickly reduced. Plots installed in sparse eucalypt and oak sites showed significant differences between plots ($p<0.05$) (results not shown). Thus in the sparse eucalypt stand, total overland flow over the 2-year period was higher at SE3 (5.9 mm) than at SE1 (1.4 mm) and SE2 (2.9 mm). In oak woodland, overland flow was lower at O1 than at O2 and O3 (2-year totals of 1.9 mm, 4.3 mm and 3.2 mm, respectively).

Median overland flow amount increased significantly with period rainfall (amount and intensity) and throughfall (Table 2), but the strength of correlations varied with woodland type. Dense eucalypt plantation exhibited stronger correlations between overland flow and rainfall variables than the other woodland types (DE: r=0.61 and 0.62, SE: r=0.44 and 0.34, and O: r=0.53 and 0.27 for rainfall amount and I_{30}, respectively, $p<0.01$). Oak woodland showed stronger correlations than eucalypt plantations between overland flow and throughfall amount (r=0.48, 0.46 and 0.60 for DE, SE and O stands, respectively, $p<0.01$), as well as with 30-day antecedent rainfall (r=0.43 and 0.26 for O and SE, $p<0.01$, no significant correlation for DE).

Generally, overland flow amount from all the plots correlated significantly neither with hydrophobicity nor soil moisture content ($p>0.05$, Table 2). In the plots installed in oak woodland, as well as in sparse eucalypt plantations, however, overland flow increased with soil moisture content, although correlation coefficients were weak (r=0.21 and 0.29, respectively, $p<0.05$).

5 Discussion

5.1 Temporal patterns of hydrological properties and woodland type

5.1.1 Throughfall

Despite the reported important role of vegetation structure and architecture in influencing throughfall amount (Návar, 1993; Levia and Herwitz, 2005; Levia et al., 2010; Livesley et al., 2014), no significant differences in exploratory throughfall data were identified between the different woodland types in *Ribeira dos Covões*. This may be due to different characteristics of the three types offsetting each other. Thus the larger scrub cover of the sparse eucalypt stand, which extended above throughfall gauges, may be the reason for its slightly lower throughfall (87%) than in the dense eucalypt plantation (92%) with its limited underbrush cover (Table 1). As throughfall measurements were made ~30 cm above the soil surface, however, interception by scrub less than 30 cm high would be missed and actual throughfall would be smaller than the values recorded.

In eucalypt plantations in *Ribeira dos Covões*, the median throughfall of 92%, at the higher end of the range of values (58-92%) reported by Valente et al. (1997) for *Eucalyptus globulus* Labill. stands elsewhere in Portugal and higher than the values (85-88%) for the same species reviewed by Llorens and Domingo (2007). In shrubs and bushes (the dominant land cover under sparse eucalypt stand in the study catchment), a mean throughfall of about 49% has been reported (Llorens and Domingo, 2007). Despite, to the authors' knowledge, no throughfall measurements having been previously undertaken in *Q. robur*, *Q. faginea* or *Q. suber* (the forest species found in the oak stand within the catchment), the results from *Ribeira dos Covões* (median of 92%) are higher than those reported for *Q. cerris L.* (85-89%), *Q. pyrenaica*, (83-86%), *Q. coccifera* (55%) and *Q. ilex* (60-78%) (Llorens and Domingo, 2007).

The relationships found between throughfall and rainfall amount and intensity tallies with findings of previous studies (e.g. Gash, 1979; Ferreira, 1996; Shachnovich et al., 2008; André et al., 2011). Smaller rainstorms (< 3.7mm) could have been fully or mostly intercepted by vegetation (<3.7 mm), but with increasing storm rainfall and wet antecedent conditions, canopy storage exceedance leads to enhanced percentage throughfall values, as reported elsewhere (Gash, 1979; Crockford and Richardson, 2000; Eisenbies et al., 2007; Bathurst et al., 2011). This may explain the very high throughfall in wetter measurement periods, such as 2nd April 2011 - 5th March 2012, which included some large rainstorm events.

5.1.2 Hydrophobicity

In *Ribeira dos Covões*, soil hydrophobicity was high and resistant to breakdown in eucalypt stands (particularly in the dense plantation), as widely reported previously (e.g. Doerr et al., 1996; Ferreira et al., 2000; Keizer et al., 2005; Keizer et al., 2008; Santos et al., 2013). In *Ribeira dos Covões,* however, hydrophobicity disappeared after 113 mm rain (period 11), whereas Ferreira et al. (2000) found hydrophobicity persisted after 200 mm rainfall in an area of schist soils farther north in Portugal. The recorded increase in spatial extent (frequency) and severity of hydrophobicity under eucalypt stands with soil depth, and the greater temporal variability at the soil surface than below it, accords with the findings of Keizer et al. (2005) for similar plantations in the coastal zone of central Portugal. The increase in hydrophobicity with soil depth, however, contrasts with the findings of Santos et al. (2013) in similar plantations but on schist soils in Portugal. Two possible reasons for the increase with depth are: (1) hydrophobic exudates being leached and precipitated in the subsoil during storm events, as reported by Doerr et al. (2000); and (2) hydrophobic conditions at depth being enhanced by greater preferential flow and less water infiltrating permeating into matrix soil at depth than at the soil surface.

Under the oak woodland, the relatively low severity and persistence of hydrophobicity recorded accord with the findings of Cerdà and Doerr (2005) for *Q. coccifera* in south-eastern Spain. However, the similar hydrophobicity found between soil depths in *Ribeira dos Covões* is in contrast to the progressive decrease described for oakwood soils in northeast Spain (Badía et al., 2013).

The recorded differences in hydrophobicity severity and persistence between woodland types in *Ribeira dos Covões* (dense eucalypt > sparse eucalypt > oak) may in part be linked to vegetation type and density, but could also be linked to soil texture differences. Hydrophobicity is more frequently associated with coarse- than fine-textured soils (DeBano, 1991; Cerdà and Doerr, 2007; Martínez-Zavala and Jordán-López, 2009) and can be reduced by small increases in clay content, depending on the clay type (McKissock et al., 2000). This could enhance the hydrophobicity on the sandier eucalypt locations on sandstone compared with the loamy oak woodland sites on limestone in the *Ribeira dos Covões* catchment.

The seasonal hydrophobicity pattern characterized by greater severity and spatial extent in dry periods, and lower under wet settings, has been widely reported elsewhere (Dekker and Ritsema, 1994; DeBano, 2000; Doerr et al., 2000; Ferreira et al., 2000; Keizer et al., 2005; Santos et al., 2013) and is clearly linked to the antecedent (including seasonal) rainfall pattern. The significant inverse correlations found between hydrophobicity and antecedent rainfall were also recorded by Buczko et al. (2007), but not by Santos et al. (2013) for other eucalypt sites in Portugal.

5.1.3 Soil moisture content

The higher soil moisture content recorded under oak than in the two eucalypt stands may be associated with higher water retention by the finer-textured soil overlying limestone bedrock compared with the coarser sandstone soils of the eucalypt areas. The higher soil moisture content under oak, however, could also result from: (1) more effective ponding by underlying bedrock in the shallower soil (<0.4 m on limestone as opposed to >3 m in sandstone), as found elsewhere (Maeda et al., 2006; Hardie et al., 2012; Yang et al., 2012); (2) the lower slope angles of the oak woodland site (Table 1, as reported elsewhere by Zhu and Lin (2011); (3) the lower position of oak plots on the hillslope (Table 1), leading to more effective moisture accumulation and retention than upslope (Kim, 2009; Ridolfi et al., 2003); and (4) the presence of a few relict stone walls in the oak woodland which may have increased water retention, as recorded elsewhere by Yang et al. (2012).

In order to assess the importance of topography, particularly the slope and upslope areas that can contribute with overland flow, on soil moisture differences between woodland types, Topographic Wetness Index (TWI) was calculated for the catchment area, using the method described by Pei et al. (2010). Although in *Ribeira dos Covões* catchment TWI reaches 21, TWI values for the woodland plots do not exceed 5, highlighting the lower probability of saturation excess overland flow. Nevertheless, the differences in TWI values between the sparse eucalyptus (1-2) dense eucalyptus (2-3) and oak woodland plots (4-5) may explain the greatest soil moisture content being measured at the oak woodland sites.

The higher soil moisture recorded under oak than eucalypt could also be linked to factors driven by vegetation, such as transpiration and hydrophobicity (less intense and less frequent in oak woodland soil). Daily transpiration from a mature *Eucalyptus globulus* Labill. stand in Portugal varied between 0.5 and 3.6 mm day^{-1} during a spring-summer period (David et al., 1997), although in south-eastern Australia, Forrester et al. (2010) reported transpiration rates in eucalyptus plantations varying from 0.4 mm day^{-1} in two-year-old stands to 1.6–1.9 mm day^{-1} in stands aged 5–7 years. Lower transpiration rates of 1,3 mm day^{-1} (464 mm a^{-1}) and 1.2 mm day^{-1} 4(453 mm a^{-1}) were reported for *Quercus ilex* L., in Catalonia, NE Spain, in valley and ridge-top locations, respectively (Sala and Tenhunen, 1996). In *Ribeira dos Covões*, the higher soil moisture content in oak than eucalypt stands, however, does not seem to result from greater water consumption by eucalypt trees, since no significant difference in soil moisture was found between dense and sparse eucalypt stands. Indeed the evapotranspiration rate of extensive scrub cover can be similar to that of eucalypt trees (Bellot et al., 2004; Hümann et al., 2011; Yang et al., 2012), which could account for the absence of significant soil moisture differences between the sparse and dense eucalypt stands. The high evapotranspiration provided by the scrub cover may also counterbalance the higher soil water retention expected at the sparse than dense eucalypt stands, due to higher silt and clay contents (Table 1).

Surface soil moisture content appears to be strongly associated with hydrophobicity pattern. Generally, soil moisture was low when hydrophobicity was most severe and high when hydrophobicity was weak or absent. In *Ribeira dos Covões*, hydrophobicity was absent above soil moisture contents of 33%, 21% and 32% in dense eucalypt, sparse eucalypt and oak woodland, respectively (Figure 6). Similarly, extreme hydrophobicity was not recorded for soil moistures above 26%, 18% and 21%, respectively, reinforcing the view of the highly resilient nature of hydrophobicity in dense eucalypt plantations. Differences in the critical moisture content for the existence of hydrophobicity between woodland types may be linked to variations in soil texture (Doerr et al., 2000) and soil organic matter (Tumer et al., 2005; Jordán et al., 2013), where the latter may be linked to species of trees and understorey vegetation. Previous studies have reported hydrophobicity for soil moisture contents of up to 22% in sandy loam soils (Doerr and Thomas, 2000), and as high as 38% in clayey soils (Dekker and Ritsema, 1994). Under eucalypt plantations in central Portugal, Santos et al. (2013) reported the dominance of strong and extreme hydrophobicity in schist soils when soil moisture content was below 14%, which is lower than for the sandstone and limestone findings in *Ribeira dos Covões*.

5.1.4 Overland flow

Runoff plots installed in *Ribeira dos Covões* recorded very low overland flow coefficients (<3%) in all the woodland types. Generally, vegetation enhances infiltration, particularly in tree stands because of their comparatively deep root systems (Calvo-Cases et al., 2003; Hümann et al., 2011; Komatsu et al., 2011). Nevertheless, the underlying bedrock can also have an important effect on slope hydrology, particularly influencing infiltration and overland flow (Hattanji and Onda, 2004; Zhang and Hiscock, 2010). Generally, coarse-textured soils associated with sandstone are usually highly permeable, allowing water to drain freely. High permeability of limestone soils has been also widely reported in areas of

Mediterranean climate (e.g. Calvo-Cases et al., 2003; Cerdà, 1997). Although bedrock differences in the study catchment may mask the influence of woodland type, significant overland flow differences were found between dense and sparse eucalyptus despite both being on sandstone, and no significant overland flow difference was identified between sparse eucalypt and oak stands despite the latter overlying limestone. Spatiotemporal variation in overland flow pattern between woodland types is thought instead to be a consequence of hydrophobicity differences, since no significant throughfall difference was found between woodland stands, and soil moisture was higher in oak soils, where overland flow was lower.

In storm events following dry weather, the most likely cause of overland flow seemed to be infiltration-excess caused by hydrophobic soils, as suggested by previous surveys of point-scale hydrological soil properties in the catchment (Ferreira et al. (2015). Thus the greater severity and persistence of hydrophobicity in the dense eucalypt plantation are considered to be the reasons for its greater overland flow percentages, especially in larger rainstorms following dry antecedent conditions. In the sparse eucalypt stand, the less severe and patchier hydrophobicity also broke down more easily as a result of rainfall (see section 4.2), thereby explaining the lower overland flow than in the dense eucalypt plantations. Nevertheless, smaller rainfall events (3.7 mm and 9.5 mm in period 23 and 25) failed to break down soil hydrophobicity in the sparse eucalyptus (Figure 3), which may explain the higher percentage overland recorded in those periods (Figure 6). In oak woodland, the low or moderate hydrophobicity and its much patchier nature would explain why infiltration-excess overland flow responses were very small even after prolonged dry weather. Differences in the breakdown resistance of hydrophobic properties may also be the reason for a stronger correlation between overland flow and rainfall in dense eucalypt plantation than in the other woodland types (see section 4.4).

Even under extreme hydrophobic conditions, however, overland flow was minor. Thus, the maximum average runoff coefficient at the dense eucalypt plots never exceeded 2.2%. This value is lower than the maximum of 10% measured in similar experimental plots in eucalypt stands in north-central Portugal following a long dry season, though for schist soils (Ferreira et al., 2000). The low overland flow under extreme hydrophobicity suggests the role of water sinks within the woodland soils. Given the relatively low soil moisture content of hydrophobic soils, infiltration would seem to occur: (1) in hydrophilic soil patches, linked to a discontinuous hydrophobic layer, particularly under oak and sparse eucalypt stands (Figure 3); and (2) via preferential flow routes provided by cracks and root holes (Urbanek et al., 2015), although stones in sufficient quantities may also promote infiltration (Urbanek and Shakesby, 2009). Several authors have reported the relevance of preferential flow patterns for water infiltration in hydrophobic soils (DeBano, 2000; Doerr et al., 2000; Buczo et al., 2006). In hydrophobic sandy and sandy loam soils elsewhere, >80% (Ritsema et al., 1997) and 86-99% (Tsukamoto and Ohta, 1988) of water movement has been attributed to preferential flow.

Limited overland flow under antecedent dry settings may be also associated with surface water retention, favoured by vegetation and litter, and micro-topographic concavities on hillslopes. Under these conditions, rainfall may stop before surface depressions had been filled. The longer concentration time required for continuous flow on long hillslopes compared with the duration of the most effective rain showers was considered by Yair and Raz-Yassif (2004) to be the cause of the low efficiency of runoff processes on slopes.

In wet conditions, particularly in the dense eucalypt plots, it was unclear whether overland flow (albeit much lower in percentage terms) was promoted by hydrophobicity-linked infiltration-excess or saturation-excess mechanisms. The persistence of subsurface hydrophobicity, in combination with a thin hydrophilic soil layer, may prevent downward water flux through the soil matrix (Doerr et al., 2000). Any infiltrated water would tend to pond above the hydrophobic layer leading to surface soil moisture build-up and possible saturation (Doerr et al., 2000; Calvo-Cases et al., 2003). Under these conditions, ponded water in the surface saturated layer may be diverted laterally as throughflow unless encountering a vertical preferential flow path, allowing it to reach soil at greater depth and perhaps enter the underlying rock.

During the wettest conditions, overland flow appears to be generated by saturation-excess in the sparse eucalypt and, particularly, oak woodland types, as the soils were hydrophilic rather than hydrophobic. In the sparse eucalypt stand, generation of saturation overland flow may also have been favoured by the greater bulk density and clay content of its soil (Table 1) and its steeper slopes (26-28º), as found elsewhere by Neris et al. (2013). Theoretically saturation overland flow should be greatest in large rainfall events, when water detention by the surface micro-topography is exceeded leading to a greater downhill flux connectivity to develop (Yang et al., 2012). Surface topography may also enhance overland flow connectivity via local rills. Thus it was observed that during this study a rill developed on plot SE3 creating a concentrated surface path for overland flow, which may account for the significantly greater overland flow in that plot compared with in plots SE1 and SE2 (see section 4.4).

In oak woodland, generation of saturation overland flow may have been favoured by the loamier and also shallower soil than in the eucalypt plantations (Table 1). These will enhance ponding and lead to subsurface lateral flow, which was observed while digging the holes for the overland flow tanks at the O2 and O3 oak plots. No ponding, however, was observed when excavating plot O1, which may be linked to its deeper, and hence less readily saturated soil. This may explain the lower runoff coefficient of plot O1 compared with O2 and O3 (see section 4.4).

Forest management activities can also affect overland flow generation. Under dense eucalypt plantation, plot DE1 had its highest runoff coefficient immediately after clear-felling. Such increases in overland flow and stream peakflow after logging have been widely reported elsewhere, where they have been linked to reduced infiltration capacities due to ground disturbance and soil compaction (Ferreira et al., 2000; Robinson et al., 2003; Eisenbies et al., 2007). In south-central Japan, partial plot thinning (43%) of a Japanese cypress forest led to an increase in runoff coefficient from 33 to 56% (Dung et al., 2012). At the catchment scale, Calder (1993) calculated a runoff increase of 3.3 mm for each percent of an area deforested, based on a world-wide database of hydrologic studies. Nonetheless, some studies have pointed out that such changes in catchment discharge are unlikely to be detected if the area affected covers less than 20-30% of the total forest cover (Scherer and Pike, 2003; Bathurst et al., 2011).

In *Ribeira dos Covões*, the fact that overland flow after clear-felling was not higher than 2.3% may be due to the thick ground cover of leaves, bark and small branches left in the harvested plot DE1, which would have enhanced water retention capacity and reduced any reduction in infiltration capacity due to splash effects. The enhancement of overland flow in

DE1 was quickly reduced, first because of low rainfall in spring and summer and secondly due to rapid regeneration of vegetation after September 2012, in response to the onset of the rainy late autumn-winter season. The timing of clear-felling may be a determining factor in overland flow impact, since felling performed during spring (rather than in late summer or autumn) allows vegetation to regenerate before autumn rains, minimizing overland flow impacts.

5.2 Implications for catchment streamflow and peri-urban catchment planning

The low overland flow amounts and percentages recorded for all woodland types in *Ribeira dos Covões* over the 2-year period supports the widespread notion of high soil permeability associated with forest vegetation. Nevertheless, different woodland types had distinct effects on overland flow amount and on its temporal pattern. Dense eucalypt plantations provided greater overland flow, mostly produced in dry settings as a result of great severity and resistance of soil hydrophobicity. However, that little overland flow resulted even under extreme soil hydrophobicity highlights the dominance of vertical water fluxes via preferential flow pathways. In oak woodland, and to a lesser extent in the sparse eucalypt stand, overland flow is mostly produced in prolonged rainfall events during wet weather conditions.

Overland flow responses, however, tend to diminish with increasing contributing area (van de Giesen et al., 2000, 2005; Ferreira et al., 2011; Chamizo et al., 2012). Based on measurements of soil hydrological properties at point-scale, Ferreira et al. (2015) suggested that woodland areas in *Ribeira dos Covões* could be an important source of overland flow in storm events during and immediately following the summer dry season and other prolonged dry periods. The very low runoff coefficients of the current plot-scale results in the same catchment demonstrates that the inverse relationship between overland flow and contributing area can be marked even with relatively small changes in area. This tallies with the findings of van de Giesen et al. (2005), who recorded a decrease of 40–75% in overland flow from short (1.25 m) to long plots (12 m). On the other hand, Mounirou et al. (2012) reported similar runoff amounts from 50 and 150 m^2 plots, though both were significantly lower than the smallest plot (1 m^2) used. In an experimental study, Chamizo et al. (2012) found an optimal plot length of 20 m to determine runoff and sediment export rates representative of a catchment. At a much larger spatial scale, Cerdan et al. (2004) recorded a strong decrease in mean runoff coefficients with increasing area in studies performed at larger scales: three times lower for 90 ha than 450 m^2, and ten times for 1100 ha than 90 ha.

Decreasing overland flow with increasing slope length is usually explained with greater opportunity for water infiltration on long than on short slopes (van de Giesen et al., 2005). It has also been attributed to increased soil heterogeneity with area, in terms of greater spatial variability in soil infiltration capacity (Cerdan et al., 2004; Mounirou et al., 2012), wettable patches and macropores, which can act as sinks for water (Calvo-Cases et al., 2003; Güntner and Bronstert, 2004; Nasta et al., 2009), as well as the temporal dynamics of the rainfall–runoff events (van de Giesen et al., 2005). Some authors have argued that spatial variability only has a scale-related effect on total runoff during relatively short rainfall events (van de Giesen et al., 2005; Mounirou et al., 2012). In *Ribeira dos Covões*, considering the small amounts of overland flow generated under woodland land-use even for relatively small runoff plots, it can be concluded that the generation in woodland areas of sufficiently continuous overland flow able to reach valley floors and channels would be rare. It would also suggest that patches of all three types of woodland could act as sinks for overland flow generated on upslope impervious urban surfaces.

The question remains, however, about overland flow responses in rainfall events more extreme than those recorded in the two-year study. The highest daily rainfall recorded in the monitoring period was only 48 mm, which is less than a 2-year return period event (Brandão et al., 2001). On 25th October 2006, however, following a period of very wet antecedent weather, a daily rainfall of 102 mm was recorded at Bencanta-Coimbra with a maximum hourly intensity of 56 mm leading to major flooding of the *Ribeira dos Covões*. According to Brandão et al. (2001), daily rainfall events of 94 mm and 112 mm at Coimbra have return periods of 10- and 50-years, respectively. The contribution from woodland areas to the 2006 flood is unknown and can only be surmised. As the 25th October rainstorm followed a prolonged period of wet weather, it is highly likely that even in the dense eucalyptus the soil would have been largely hydrophilic and any overland flow generated in all three woodland types would probably have been saturation-excess in type. It is clearly possible that in such an extreme event the percentage saturation overland flow generated from all three woodland areas would have been much greater than the maxima of <3% recorded in the current study. Also a greater proportion would have been transferred to downslope areas, since surface water retention capacities provided by litter and micro-topographic concavities would have been exceeded. Although some studies have emphasized the limited storage capacity of forested terrain during larger storms and its minor role in flood protection (Bathurst et al., 2011; Eisenbies et al., 2007), it is considered that the high infiltration capacities of the soils of the catchment when hydrophilic (Ferreira et al., 2015) and the high storage capacities of the comparatively deep (>3m) sandstone soils of the dense and sparse eucalyptus sites would have limited the overland flow contribution from the eucalyptus woodland areas and retained some sink role for urban runoff, with really high percentages of overland flow restricted to the oak woodland areas with their shallow, easily saturated soils. It is arguable, however, that the overland flow contribution from the dense eucalypt areas would have been much higher if an extreme storm of the magnitude of the 25th October 2006 event had occurred after dry antecedent weather when the dense eucalyptus soil would have been highly hydrophobic rather than hydrophilic. Clearly the timing of extreme events in relation to woodland and soil types in a peri-urban catchment is of crucial significance to the size of overland flow responses and degree of downstream flooding.

The hydrological responses of different woodland types in extreme events, however, clearly needs further investigation. Additional plot monitoring in *Ribeira dos Covões* is needed to cover overland flow responses in larger storm events than occurred in the study period after dry and wet antecedent conditions if more reliable inferences concerning the influence of woodland types within peri-urban mosaics on flood risk are to be drawn.

Woodland is the dominant land-use in *Ribeira dos Covões* catchment, followed by urban surfaces, which in some places interrupts woodland patches (Figure 1). The increase in impervious area and catchment discharge with additional urbanization in recent years is expected to continue given the future urban development already approved (Ferreira et al., 2013). The small amounts of overland flow generated in all three woodland types demonstrates that patches of woodland can provide potential sinks for overland flow generated from upslope impervious urban surfaces if they naturally or are directed to flow into such patches. The magnitude and effectiveness of such a sink role in a peri-urban catchment, will be affected (1) by the type of woodland, given the differences in overland flow mechanisms and responses shown by this study, (2) their distribution within the catchment in relation to upslope urban surfaces and (3) the extent to which upslope urban runoff flows into them. It is argued here that knowledge of the impact of woodland areas, and particularly of woodland type on temporal overland flow dynamics should be taken into consideration in integrated planning and management of catchments undergoing urban development, particularly as regards planning the type and distribution of woodland patches and the delivery of urban surface runoff into these patches. Further investigation should be carried out in order to improve understanding of the appropriate sizes and locations of distinct woodland areas within peri-urban catchments, in order to minimize the hydrologic impacts of urbanization and protect downslope urban cores from flood hazard.

6 Conclusions

In the peri-urban catchment of *Ribeira dos Covões* in central Portugal, three distinct woodland types on sandstone and limestone produced overland flow representing less than 3% of the incident rainfall, based on measurements performed on small (16 m^2) plots over 2-years of monitoring. Plots on a managed dense eucalypt stand generated significantly 2.5 times more overland flow than plots on sparse eucalypt or oak woodland on abandoned peri-urban land.

In dry conditions, hydrophobicity-linked infiltration-excess overland flow was the dominant means of downslope water movement. This process was particularly important in dense eucalypt plantations, where hydrophobicity was more extreme, spatially contiguous and resistant to breakdown with rainfall than was the case in the other two woodland types. Under hydrophobic conditions at the dense eucalyptus sites, overland flow amount strongly increased with rainfall amount and intensity, but median and individual plot overland flow coefficients attained maxima of 2.2% and 2.7%, respectively. In contrast, in the sparse eucalypt plots, their moderate hydrophobicity after dry periods was easily broken down, and percentage overland flow was greatest (albeit ≤0.5%) in smaller rainfall events when the soil failed to become wettable within the event. The weak hydrophobic properties observed in oak woodland plots led to a maximum overland flow coefficient of only 0.4% in storms following dry antecedent weather, and median plot values of 0.3% for storms during the dry season.

In periods of wet weather, however, saturation overland flow occurred most readily in oak woodland followed by sparse eucalypt stands. Relatively high soil moisture contents maintained throughout wet periods enhanced saturation overland flow, so that plot runoff coefficients reached 1.7% and 2.2% on the sparse eucalypt and oak woodland sites, respectively. At the latter, saturation was favoured by the shallow soil overlying limestone, its loamy texture and subsurface lateral flow, whereas in the sparse eucalypt stand, saturation was favoured by the high bulk density and clayey nature of the soil. In both woodland types, overland flow strongly increased with rainfall amount and soil moisture. In contrast, in the dense eucalypt plantation, median overland flow never exceeded 1.0% of rainfall in periods of wet weather.

Interception by the different woodland types was not significantly different, based on exploratory throughfall measurements performed. It is thought to have been important in reducing overland flow responses only during small rainfall events following antecedent dry weather, as throughfall was high (and interception was low) in percentage terms during large events and wet periods due to canopy saturation. In addition, surface roughness, associated with the litter layer promoted water retention and decreased lateral flow connectivity.

Important implications of this study for managing peri-urban catchments are that patches of semi-natural and managed woodland are critical in order to retain rainfall, promote infiltration and act as sinks for overland flow from upslope. In fully urbanized catchments, the lack of rainfall interception and the size, and often contiguity, of areas covered by impermeable surfaces tend to promote rapid overland flow and the possibility of flooding. Authorities concerned with catchment management and urban planning, therefore, should try to incorporate woodland patches in any development proposal not only to reduce the total runoff-generating area, but also to provide sinks for runoff produced on impermeable urban surfaces upslope. Thus, the most satisfactory compromise is likely to be a mosaic of diverse land-uses designed to disrupt overland flow connectivity. Nevertheless, the varying impact of different woodland types on overland flow processes and catchment hydrological response should also be considered. Identifying the best arrangement of such patches (e.g. type of woodland, extension and location within the landscape) while maximizing the use of land for urban development should now be a research priority. A second research need is for field data on overland flow responses within this mosaic in more extreme, potentially flood-producing rainstorms than occurred within the 2-year monitoring period of this study.

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Figure 1

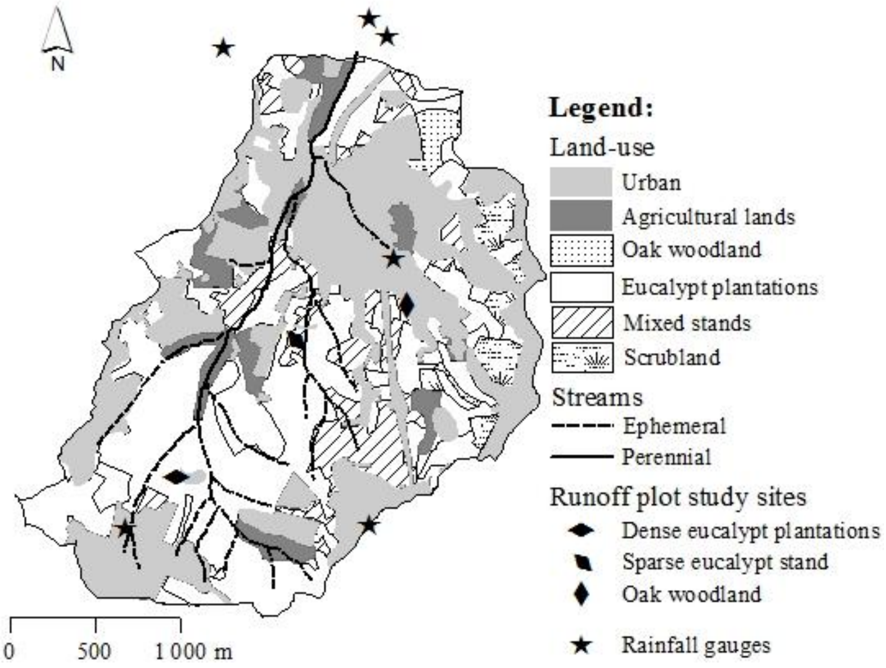

Figure 1 – *Ribeira dos Covões* catchment land-use and location of the study sites instrumented with runoff plots.

Figure 2

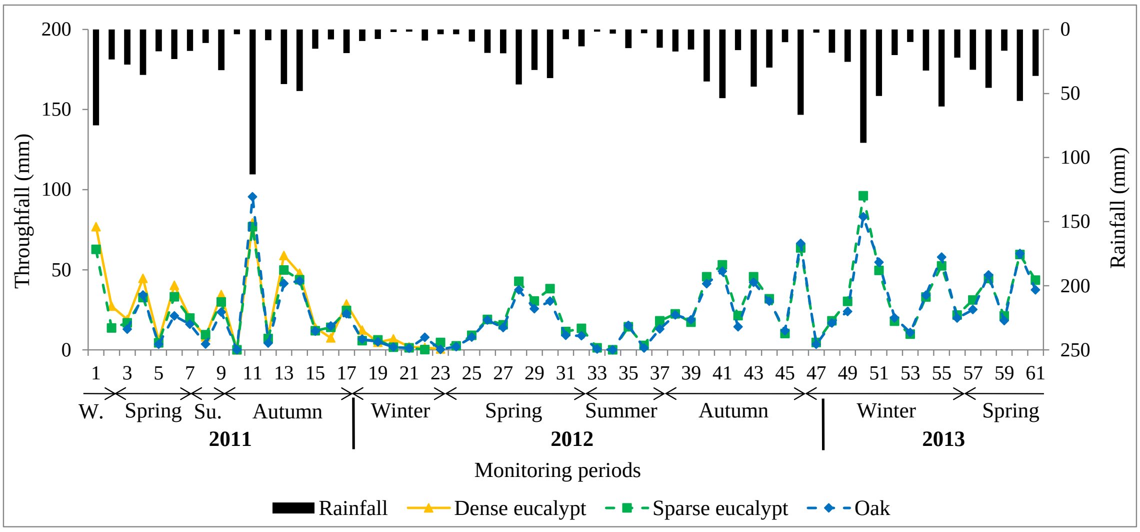

Figure 2 – Weighted average rainfall amount and median throughfall per woodland type, for the 61 measurement periods from 9th February 2011 to 14th April 2013. Throughfall results only until 5th March 2012 in dense eucalypt plantation due to collectors’ theft.

Figure 3

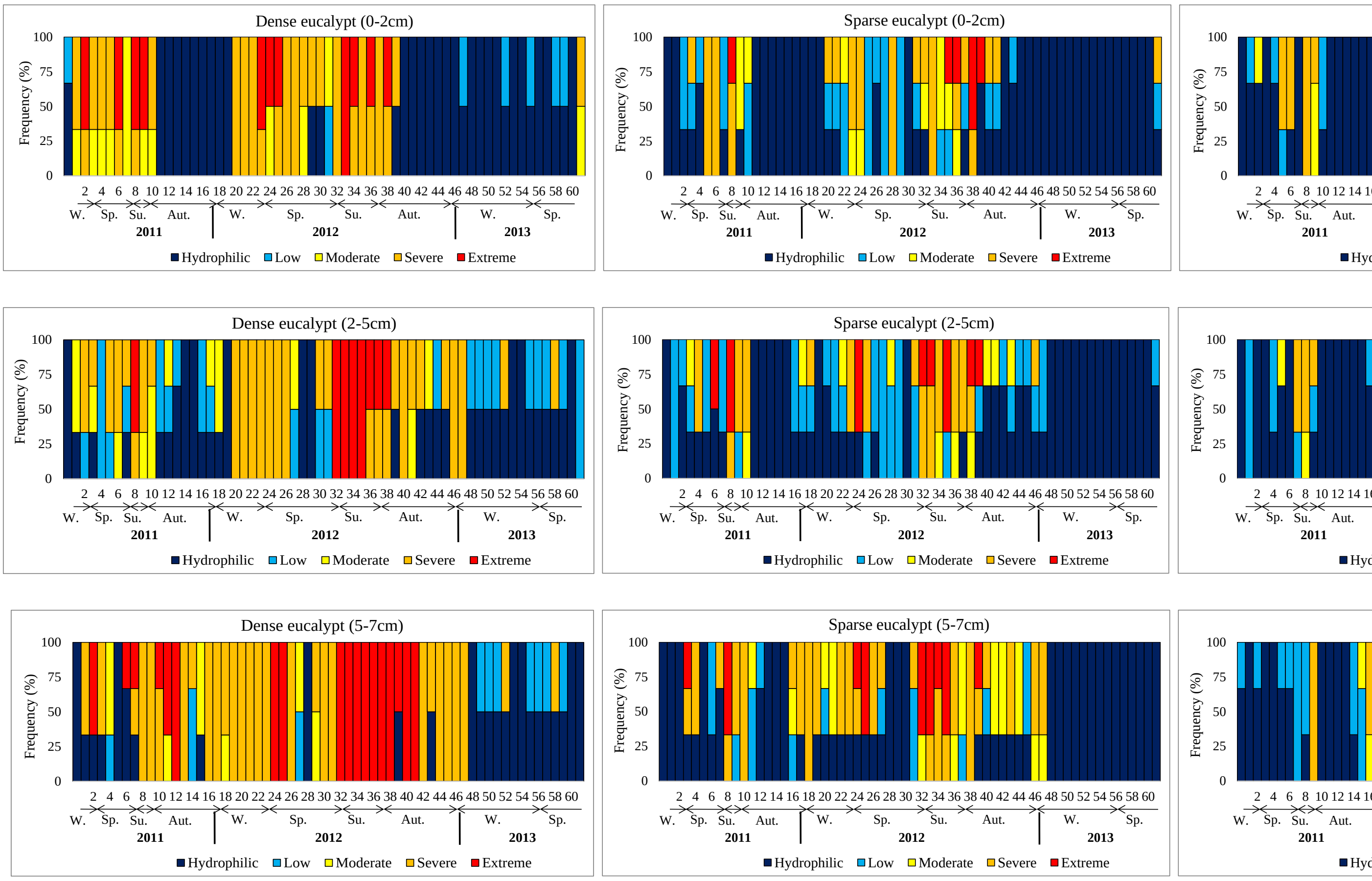

Figure 3 – Temporal variability of frequency distribution of hydrophobicity classes per woodland type and s

for the 61 measurement periods from 9th February 2011 to 14th April 2013.

Figure 4

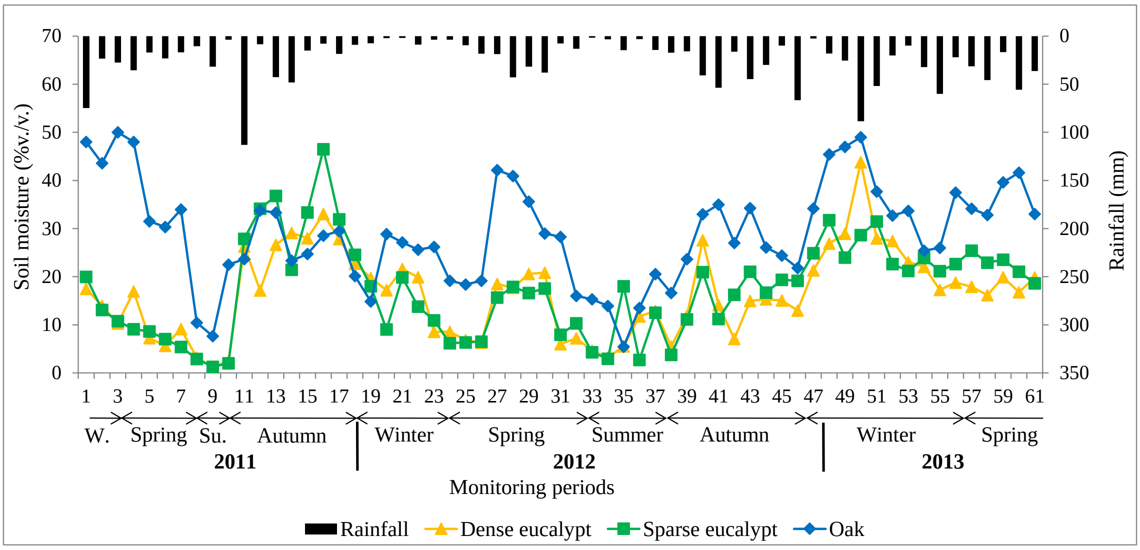

Figure 4 – Median surface soil moisture content per woodland type for the 61 measurement periods, from 9th February 2011 to 14th April 2013.

Figure 5

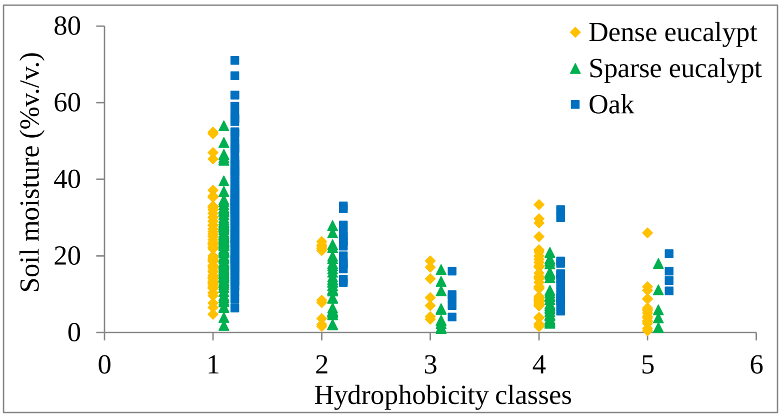

Figure 5 – Average soil moisture variability within hydrophobicity classes (1: wettable, 2: low, 3: moderate, 4: severe and 5: extreme hydrophobicity) for different forest types.

Figure 6

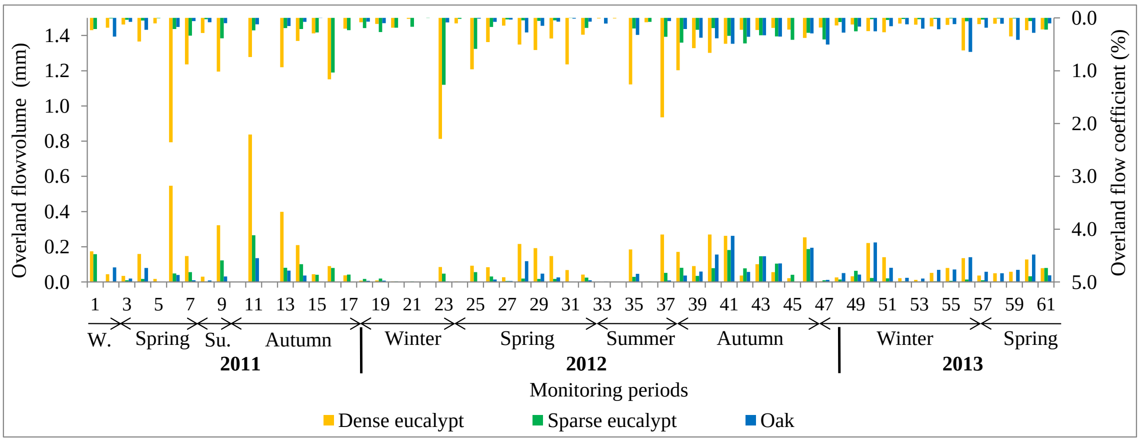

Figure 6 – Median overland flow, expressed as amount and percentage rainfall, per woodland type for the 61 measurement periods, from 9th February 2011 to 14th April 2013.

Table 1

Table 1 – Biophysical characteristics of the three study sites in *Ribeira dos Covões* catchment. S: sandy, SL:
sand.

	Woodland type	Dense eucalypt			Sparse eucalypt			
	Plot reference	DE1	DE2	DE3	SE1	SE2	SE3	O1
Vegetation and litter cover	Trees (number per ha)	800	1300	900	150			500 (canopy
	Stage of trees development (years)	Mature (~15)	Young (~5)	Young (~8)	Mature (~10)			
	Vegetation (cover, height)	15%, 0.15 m	0%	95%, 0.5 m	100%, 0.8 m	100%, 1.5 m	100%, 1 m	40%, 0.8 m
	Litter layer depth (cm)	2	5	<1	<1	2	1	1
Topography	Elevation (m)	138	132	137	105	105	105	90
	Slope aspect	W	NW	NW	NE	NE	NE	W
	Slope (°)	18	16	26	26	28	26	13
Soil properties	Lithology	Sandstone			Sandstone			
	Soil depth (m)	>2m			>2m			
	Texture	SL	S	SL	LS	LS	SL	L
	Particle size distribution (%)							
	Sand	80	95	75	44	59	65	53
	Silt	7	3	10	18	15	17	27
	Clay	13	2	15	39	26	18	20
	Organic matter (%)	8	7	9	5	4	3	7
	Bulk density (g cm^{-3})	0.74±0.38	0.69±0.23	0.64±0.11	1.28±0.24	1.13±0.29	1.24±0.40	0.80±0.29

Table 2 – Spearman rank correlation coefficients between rainfall, throughfall, overland flow and soil propert
with 0.05 and 0.01 levels of significance; n=511).

	Throughfall (mm)	Hydrophobicity			Soil moisture (%)	Ov flo
		0-2cm	2-5cm	5-10cm		
Rainfall (mm)	0.83**	-0.31**	-0.29**	-0.30**	0.25**	0
I_{30} (mm h^{-1})	0.57**	-0.13**	-0.10*	-0.09*	-0.01	0
Throughfall (mm)	-	-0.20**	-0.22**	-0.16**	0.20**	0
Hydrophobicity						
0-2cm	-0.20**	-	0.68**	0.42**	-0.51**	-
2-5cm	-0.22**	0.68**	-	0.72**	-0.52**	-
5-10cm	-0.16**	0.42**	0.72**	-	-0.42**	(
Soil moisture (%)	0.20**	-0.51**	-0.52**	-0.42**	-	-
Soil texture						
Sand (%)	-	0.25**	0.28**	0.28**	-0.19**	0
Silt (%)	-	-0.26**	-0.30**	-0.36**	-0.20**	-0
Clay (%)	-	-0.15**	-0.18**	-0.23**	-0.09*	-0
Organic matter (%)	-	0.14**	0.16**	0.22**	0.04	0
Bulk density (g cm^{-3})	-	-0.06	-0.05	-0.07	-0.21**	-0

Slope (°)	0.09	0.07	0.014**	0.13*	-0.32**