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### Paper:

Walsh, R. (2016). Differences in overland flow, hydrophobicity and soil moisture dynamics between Mediterranean woodland types in a peri-urban catchment in Portugal. *Journal of Hydrology*, 533, 473-485.

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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 km<sup>2</sup>) 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<sup>2</sup> 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](mailto:carla.ssf@gmail.com), [cferreira@esac.pt](mailto: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

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(Signature of corresponding author on behalf of all authors)  
9<sup>th</sup> 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 than what is observed over a patch. My own field experience indicates that overland runoff upstream may well infiltrate 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 14<sup>th</sup> December 2012, 43.1 mm on 7<sup>th</sup> March 2013, 29.0 mm on 19<sup>th</sup> January 2013 and 26.8 mm on 2<sup>nd</sup> November 2011. These falls are well below 102 mm fall recorded on 25<sup>th</sup> October 2006, which led to floods within the catchment.” (lines 276-280)

Although minor, the temporal pattern 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 25<sup>th</sup> 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 25<sup>th</sup> 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)



## 21 Abstract

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

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

47

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

50

## 51 1. Introduction

52 Forest covers 31% of the world's land surface (FAO, 2010) and 35% of mainland Portugal  
53 (ICNF, 2013). ~~In recent decades, g~~Globally forest cover has increased in recent decades as  
54 a result of greater demand for timber and environmental concerns (e.g. Robinson et al.,  
55 2003). However, ~~forest cover has decreased~~ in peri-urban catchments located in previously  
56 forested terrain, forest cover has decreased where urbanization has led to progressive  
57 deforestation and forest fragmentation (Nowak, 2006) and remaining woodland can often  
58 change in character because of altered or abandoned ~~edment of~~ management.

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

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

75 | Hydrophobicity, induced by substances (especially some resins and waxes) produced by  
76 | some vegetation species (Dekker and Ritsema, 1994), has become increasingly recognized  
77 | as an important soil property that can affect overland flow in forest soils, particularly in  
78 | seasonally dry environments. Thus in a ~~previously rip-ploughed~~ eucalypt plantation area of  
79 | north-central Portugal, temporal changes in hydrophobicity ~~was were~~ found to explain 74%  
80 | of overland flow variation (Ferreira et al., 2000). ~~Hydrophobicity is induced by various~~  
81 | ~~hydrophobic compounds, such as distinct resins and waxes, which restrict infiltration into~~  
82 | ~~soils (Dekker and Ritsema, 1994)~~. Many studies have demonstrated differences in degrees  
83 | of hydrophobicity between different vegetation types (e.g. DeBano, 2000; Zavala et al.,  
84 | 2009; Lozano et al., 2013). Eucalypt stands are renowned for inducing high levels of  
85 | hydrophobicity (Doerr et al., 1996; Ferreira et al., 2000; Santos et al., 2013), with. ~~In~~  
86 | ~~Portugal~~, some studies in Portugal have report linked greater overland flow produced  
87 | under eucalypt than pine plantations ~~caused by~~ with enhanced soil hydrophobicity under  
88 | eucalyptus (Ferreira et al., 2000; Keizer et al., 2005). In contrast, ~~but~~ little is known about  
89 | ~~the~~ overland flow in processes of Mediterranean oak stands, particularly in wet  
90 | Mediterranean climates. This is important as differences in overland flow between distinct

91 forest stands can contribute to variations in total streamflow and the stormflow component  
92 with forest land-use change (Fritsch, 1993; Grip et al., 2005). ~~However, in the literature,~~  
93 ~~whereas in many cases~~ streamflow differences in areas subject to forest ~~specie~~cover  
94 changes are ~~mostly~~ attributed to evapotranspiration adjustments (e.g. Swank and Douglass,  
95 1974; Otero et al., 1994). ~~For example, Otero et al. (1994) reported reduced streamflow in~~  
96 ~~Chile with conversion of native forest to fast-growing plantations of *Pinus radiata*. In the~~  
97 ~~southern Appalachians, the conversion of a deciduous hardwood catchment to a *Pinus*~~  
98 ~~*strobus* L. stand (eastern white pine), led to a 20% reduction of streamflow, attributed to the~~  
99 ~~greater vegetative surface area of *Pinus strobus* (Swank and Douglass, 1974).~~

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

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



114 | ~~are tend to be often~~ characterized by a mosaic of different urban and non-urban land-uses,  
115 | including woodland types on areas of altered or abandoned forest or agricultural  
116 | management, as well as patches of pre-existing managed forest. Theoretically in such  
117 | catchments, patches of forest types with permeable soil can break flow connectivity over  
118 | the landscape and act as sinks to overland flow from upslope urban surfaces, whereas any  
119 | overland flow generated on forest types with soils of lower permeability may reach  
120 | downslope urban surfaces and represent an additional contribution to the urban flood  
121 | hazard. Such peri-urban situations, particularly in areas of Mediterranean climate, have  
122 | been little studied, ~~which provide varying sources and sinks of overland flow~~ (Ferreira et  
123 | al., ~~2014~~2015).

124 | This paper investigates the influence of three different types of woodland occurring within  
125 | a peri-urban mosaic on overland flow generation in the Ribeira dos Covões catchment in  
126 | an area of Mediterranean climate in central Portugal. Two of the woodland types  
127 | investigated ((i) sparse eucalyptus adjacent to eucalyptus plantations and (ii) oak woodland)  
128 | have been strongly influenced by semi-abandonment of land with peri-urbanization,  
129 | whereas the third comprises pre-existing managed dense eucalyptus. A previous  
130 | investigation in the same catchment (Ferreira et al. (2015) investigated temporal  
131 | changes differences in soil properties (soil matrix infiltration capacity, soil moisture  
132 | content and hydrophobicity and soil matrix infiltration capacity) at a network of points in  
133 | different landscape units found in the found in a Portuguese peri-urban catchment  
134 | (woodland-sandstone, woodland-limestone, agriculture-sandstone, agriculture-  
135 | limestone, urban-sandstone and urban-limestone); it then and discussed their potential  
136 | impacts on overland flow within the catchment processes. Results suggested highlighted  
137 | that woodland areas might provide important sinks of overland flow during wet periods

138 ~~due to the high~~ great infiltration capacities recorded on their soils, but might ~~also~~ act  
139 ~~contribute~~ as overland flow sources in storms following ~~during~~ dry periods (especially in  
140 summer) because of the hydrophobic nature of the soil matrix. The current paper tests  
141 these tentative suggestions of the previous paper by using a plot-scale monitoring approach  
142 to assess temporal differences in overland flow generation, and its influencing factors,  
143 between the sparse eucalyptus, oak woodland and managed dense eucalyptus woodland  
144 types over a two-year period. The focus is on the roles played by differing temporal  
145 regimes in hydrophobicity and soil moisture of the three woodland types studied. The  
146 implications of the results for planning land-use mosaics in peri-urban catchments in such  
147 environments are also explored.

148

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

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

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

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

165

## 166 **2. Study area**

167 The study was carried out in the peri-urban *Ribeira dos Covões* catchment (8°27'W,  
168 40°13'N), located 3km NW of Coimbra, the largest city in central Portugal. The ~~is~~  
169 catchment ~~(Figure 1) is (6.2km<sup>2</sup>) in area,~~ is aligned S-N and ranges in altitude from 34 to  
170 205 m a.s.l. The area has a ~~sub-humid~~-Mediterranean climate, with a mean annual  
171 temperature of 15°C and an average annual rainfall of 892 mm over the period 1941-2000  
172 recorded at Coimbra-Bencanta (national meteorological weather station 12G/02UG), sited  
173 0.5 km north of the study catchment. A ~~distinct~~-dry and hot season occurs from June to  
174 August (8% of annual rainfall), whereas the rainiest period is ~~frombetween~~ November  
175 ~~toand~~ March (61% of annual rainfall). ~~Relatively small r~~Rainfall events are mostly  
176 ~~small~~dominant over the year, with 83% of daily rainfalls ~~in 2001-13~~between 2001 and 2013  
177 at Coimbra-Bencanta being  $\leq 10$  mm. ~~Annual m~~Maximum daily rainfalls ~~inover the same~~  
178 ~~2001-13 period~~ ranged ~~frombetween~~ 20 mm ~~toand~~ 102 mm. The catchment is underlain by  
179 sandstone (57%) and limestone (43%). Soils developed on sandstone are classified as  
180 Fluvisols and Podsol, following the WRB (2006) classification, and are generally deep (>3  
181 m), while ~~the~~ Leptic Cambisols found on limestone slopes are typically shallow (<0.4 m)  
182 (Pato, 2007).

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

191 Currently, the woodland area consists mainly of *Eucalyptus globulus* Labill. plantations  
192 (55%), but with some mixed stands of eucalypt and pine (29%), ~~scrublands~~ (15%) and  
193 relict oak woodland composed of *Quercus robur* L., *Q. faginea broteroi* and *Q. suber* L.  
194 trees (1%) (Figure 1). Generally, eucalypt plantations occur on sandstone, but some areas,  
195 abandoned following logging, are now covered by sparse eucalypt stands with a dense  
196 scrub understorey. On limestone, vegetated areas are largely covered by shrubs (e.g.  
197 *Pistacia lentiscus*, *Spartium junceum*, *Cistus crispus*, *Ulex jussiaei*), but with semi-natural  
198 oak stands. In the oak area, a number of stone walls have survived from an earlier  
199 agricultural land-use, mainly olive plantations. Thus both the sparse eucalyptus and oak  
200 woodland types have been strongly influenced by semi-abandonment of land with peri-  
201 urbanization.

202

### 203 3. Methodology

#### 204 3.1 Experimental design and measurements

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

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

223 Each plot was further equipped with five manual throughfall gauges to give an approximate  
224 idea of differences between woodland types. The throughfall gauges comprised funnels (20  
225 cm in diameter) connected to a storage bottle (3-litre capacity), installed at the soil surface  
226 within half-buried PVC pipes (20 cm in diameter and 30 cm long). The five gauges were  
227 placed randomly 0.5-2m outside the plot boundaries beneath the tree and/or scrub

228 vegetation. Rainfall data were based on weighted-average results of five tipping-bucket rain  
229 gauges installed in open areas within and near the catchment (Figure 1). Given the  
230 relatively small number of throughfall gauges, throughfall measurements only represent  
231 exploratory data to give a comparison between woodland types; ~~and~~ water inputs to the  
232 plots were based on rainfall data.

233 Hydrophobicity and soil moisture content were measured on undisturbed land adjacent to  
234 each plot. Soil hydrophobicity was assessed at 0-2 cm, 2-5 cm and 5-7 cm depths along two  
235 1-m transects at either side of each plot using the ‘Molarity of an Ethanol Droplet test’  
236 (Doerr, 1998). Sets of fifteen droplets of increasing ethanol concentration were applied  
237 along each transect until infiltration of at least eight droplets of the same concentration  
238 occurred within 5 seconds. The results for each transect were classified according to the  
239 following five repellency ratings and associated ethanol concentrations: wettable (0%); low  
240 (1, 3 and 5%); moderate (8.5 and 13%); severe (18 and 24 %); and extreme (36 and >36 %)  
241 hydrophobicity. Gravimetric soil moisture content was determined in the laboratory by  
242 oven-drying at 105°C for 24h. On each measurement occasion, this was done using one  
243 composite soil sample per plot (0-5cm soil depth), which was obtained by mixing 10  
244 samples collected randomly on undisturbed land around each plot. Gravimetric was  
245 converted into volumetric water content using the mean soil bulk density of each site,  
246 calculated from 11 random soil samples of  $\sim 143 \text{ cm}^3$  volume collected near to each plot,  
247 using purpose-built soil ring samplers of 5 cm diameter and 7.3 cm length.

248 Overland flow, throughfall, hydrophobicity and soil moisture were measured on 61  
249 occasions at 1- to 2-week intervals (depending on previous rainfall) over the ~~two-2-~~years  
250 from 9<sup>th</sup> February 2011 to 14<sup>th</sup> April 2013. In March 2012, part of the dense eucalypt site

251 was clear-felled, destroying plot DE2 (where monitoring was abandoned) and affecting tree  
252 interception at plot DE1. Owing to vandalism and theft of equipment on several occasions  
253 after clear-felling, throughfall measurement at the dense eucalypt plot locations was also  
254 abandoned from mid-2012 onwards.

255

### 256 **3.2 Data analysis**

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

269

## 270 **4. Results and Analysis**

### 271 **4.1 Rainfall**

272 Overall, rainfall over the 2-year monitoring period (totalling 1581.7 mm) was relatively  
273 lowdry, with annual rainfalls in 2011 and 2012 being 18 and 38% respectively below the  
274 long-term (1941-2000) average of 892 mm. The 61 measurement periods differed markedly  
275 in total rainfall amount (1.8-113 mm) (Figure 2), number of rainfall days (2-12) and  
276 maximum 30-min rainfall intensity ( $I_{30}$ : 0.6-24.8 mm h<sup>-1</sup>), but none represented extreme  
277 rainfall events (all beneath 2-years Intensity-Duration-Frequency curves foref Coimbra  
278 (Brandão et al., 2001). The seasonal pattern was typically Mediterranean, with distinctly  
279 lower rainfall in summer (4% of total rainfall fell in June to August) compared with 35% in  
280 autumn, 32% in winter and 28% in spring. Nevertheless, there was also a very dry period in  
281 winter 2011/12 from 21<sup>st</sup> December 2011 to 20<sup>th</sup> March 2012 (37 mm). In contrast,  
282 November 2011, January 2013 and March 2013 were wetter than the long-term 1941-2000  
283 averages ~~(1941-2000)~~ (163 vs 111 mm, 166 vs 116 mm and 228 vs 87 mm, respectively).  
284 In total there were 333 days with rain during the 2-year monitoring period, with 47 daily  
285 falls exceeding 10.0 mm, of which four exceeded 25.0 mm. The highest daily falls were  
286 48.1 mm on 14<sup>th</sup> December 2012, 43.1 mm on 7<sup>th</sup> March 2013, 29.0 mm on 19<sup>th</sup> January  
287 2013 and 26.8 mm on 2<sup>nd</sup> November 2011. These falls are well below 102 mm fall  
288 recorded on 25<sup>th</sup> October 2006, which led to floods within the catchment.

289

## 290 **4.2 Throughfall**

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



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

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

306

## 307 **4.2 Hydrophobicity**

308 In all soil layers, hydrophobicity was most severe and frequent in the dense eucalypt  
309 plantations, intermediate in the sparse eucalypt stand and least ~~west~~ in the oak woodland  
310 ( $p < 0.05$ ) (Figure 3). In the oak stand, hydrophobicity was absent on many measurement  
311 dates (69% of occasions at both 0-2 cm and 2-5 cm and 48% of occasions at 5-7 cm) and  
312 was largely of low or moderate severity when present. In this woodland type,  
313 hydrophobicity was mainly transient in nature, being recorded in all the sampling sites only  
314 on 14%, 13% and 17% of monitoring occasions, at 0-2 cm, 2-5 cm and 5-7 cm depth,  
315 respectively. In the sparse eucalypt site, hydrophobicity showed the greatest spatial and  
316 temporal variation; hydrophilic conditions were dominant on 49%, 34% and 39% of the  
317 measurement dates, at 0-2 cm, 2-5 cm and 5-7 cm, respectively, but hydrophobicity was

318 | mostly moderate to severe -when present. As in oak woodland, the sparse eucalypt stand  
319 | showed a transient and patchy hydrophobic pattern, with widespread hydrophobicity  
320 | recorded ~~in~~ just 26% of the 61 measurement ~~occasions~~~~periods~~ at 0-2 cm and 5-7 cm and  
321 | on 24% of occasions at 2-5 cm depth. In contrast, in dense eucalypt plantations, hydrophilic  
322 | conditions were only observed on 41%, 15% and 13% of occasions, at 0-2 cm, 2-5 cm and  
323 | 5-7 cm depth respectively, with severe to extreme hydrophobic properties being dominant  
324 | and widespread, ~~forming a continuous surface area~~ on 53%, 55% and 70% respectively of  
325 | occasions when hydrophobicity was present.

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

333 | In dense eucalypt stands, hydrophobicity increased in frequency and severity with soil  
334 | depth (differences between 0-2 cm and 5-10 cm layers,  $p < 0.05$ ). Also, ~~a greater number~~  
335 | ~~of~~~~more~~ rainstorms were required to reduce hydrophobicity levels in deeper soil. Extreme  
336 | hydrophobicity was recorded on 18%, 13% and 30% of occasions respectively at 0-2 cm, 2-  
337 | 5 cm and 5-10 cm. A similar pattern with depth occurred ~~in~~~~at~~ the sparse eucalypt site,  
338 | despite lower hydrophobicity severity and coverage (extreme hydrophobicity was recorded  
339 | ~~in~~~~on~~ 8%, 13% and 15% of occasions, at 0-2 cm, 2-5 cm and 5-10 cm depth, respectively). In  
340 | contrast to eucalypt sites, hydrophobicity did not vary significantly with soil depth in oak

341 woodland ( $p>0.05$ ), although it showed a tendency to decrease in severity but increase in  
342 temporal frequency with soil depth (Figure 3).

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

348

#### 349 **4.3 Soil moisture content**

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

353 Soil moisture content increased significantly with preceding period rainfall amount and  
354 throughfall ( $p<0.01$ ), although ~~the~~ relationships were not very strong (Table 2). It was  
355 substantially lower in summer than in other seasons ( $p<0.05$ ), with a similar median value  
356 (8%) for all woodland types. Soil moisture was much higher in autumn, winter and spring  
357 ~~increased slightly from spring, to autumn and winter (21, 24%, and 25% and 21%,~~  
358 respectively), but with variations between ~~the two~~ years. During spring, median soil  
359 moisture content was higher in 2013 (22%) than in both 2011 (16%) and 2012 (11%)  
360 ( $p<0.05$ ). In autumn, soil moisture was significantly higher in 2011 than in 2012 (28% vs  
361 17%) ( $p<0.05$ ). In winter, median soil moisture reached highest values in 2013 (26 %  
362 compared with 19% in 2011 and 20% in 2012). Generally, higher soil moisture content was

363 observed during autumn 2011 (median values of 27%, 33% and 27% for ED, EO and O,  
364 respectively), winter 2013 (median values of 23%, 24% and 36% for ED, EO and O,  
365 respectively) and spring 2013 (median values of 18%, 22% and 36% for ED, EO and O,  
366 respectively). Soil moisture content reached highest values of 37%, 32% and 49% in ED,  
367 EO and O in winter 2013, but the peak value of 47% in the EO site was attained in autumn  
368 2011.

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

374

#### 375 **4.4 Overland flow**

376 | The median plot values of overland flow amount in mm (above) and as a percentage of  
377 | rainfall (below) for each woodland type in each of the 61 measurement periods is shown in  
378 | Figure 5. Although  $\Theta$  overland flow was generated in most measurement periods (97, 92  
379 | and 89% of the occasions for dense eucalypt, sparse eucalypt and oak stands, respectively),  
380 | although runoff over the 2 years overall runoff coefficients represented less than 1% of total  
381 | rainfall over the 2 years (Figure 5).  $\Theta$  median overland flow exceeded 1% of period rainfall  
382 | on just 8, 4 and 3 occasions out of 61 for dense eucalypt, sparse eucalypt and oak sites,  
383 | respectively, and never exceeded 3% (Figure 5). Overland flow amounts (median values  
384 | for individual periods), ~~was were~~ significantly higher in the dense eucalypt plantation than  
385 | in the sparse eucalypt and oak stands ( $p < 0.05$ , Kruskal-Wallis and LSD tests) and overland

386 ~~flow over the two-year period was over twice as high in dense eucalyptus (6.9 mm, 0.43%)~~  
387 ~~than at the sparse eucalyptus (2.6 mm, 0.16%) and oak woodland (2.9 mm, 0.18%) plots.~~  
388 ~~(median overall values of 6.9 mm, 2.6 mm and 2.9 mm, respectively, over 2 years)~~  
389 ~~( $p < 0.05$ ).~~

390 Differences in the temporal pattern of overland flow were also observed between woodland  
391 stands. Dense eucalypt plantation plots generated greater percentage overland flow  
392 (medians of up to 2.2%) in rainstorms occurring ~~after dry antecedent weather in dry settings~~  
393 ~~(especially in~~ late spring, summer and at the beginning of autumn), whereas in wet  
394 conditions, ~~even in large events, it never exceeded 1.0 %.~~ was lower than 1.0%. In the  
395 sparse eucalypt stand, ~~median~~ overland flow varied ~~in contrary fashionless~~ over the year,  
396 with ~~higher values in wet weather of autumn, winter and spring and lower values in storms~~  
397 ~~following dry periods, particular in summer and early autumn. Thus the~~  
398 ~~maximum~~ ~~maximum~~ ~~greatest recorded median~~ runoff coefficients ~~of~~ was only 0.54% ~~in a~~  
399 ~~measurement period after dry weather in dry but~~ and 1.23% ~~after wet weather in wet~~  
400 ~~settings. (mainly in spring, autumn and winter periods).~~ In the dense eucalypt plantation,  
401 the highest percentage overland flow values were recorded in moderate rainfall events (4-  
402 23 mm and  $I_{30} = 3-16 \text{ mm h}^{-1}$ ), whereas in the sparse eucalypt stand highest percentage  
403 overland flow occurred in relatively small rainfall events (4-10 mm and  $I_{30} = 3-6 \text{ mm h}^{-1}$ ).  
404 ~~Again, In~~ contrast to ~~the dense both~~ eucalypt ~~plots~~ sites, ~~overland flow~~ in oak woodland  
405 ~~overland flow~~ was mainly produced after the wettest antecedent weather and soil moisture  
406 conditions, attaining higher values ~~mostly~~ ~~ainly~~ in larger rainfall events (>10 mm), ~~which~~  
407 ~~were mostly experienced~~ in winter and spring 2013, the wettest ~~measurement periods in part~~  
408 ~~of~~ the 2-year study. ~~In the oak woodland, however, Even under the wettest conditions,~~  
409 ~~however, the highest recorded runoff coefficient only reached 2.2% in the oak stand (but~~

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

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

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

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

438

## 439 5 Discussion

### 440 5.1 ~~Spatio~~Temporal patterns of hydrological properties and woodland type

#### 441 5.1.1 Throughfall

442 Despite the reported important role of vegetation structure and architecture in influencing  
443 throughfall amount (Návar, 1993; Levia and Herwitz, 2005; Levia et al., 2010; Livesley et  
444 al., 2014), no significant differences in exploratory throughfall data were identified between  
445 the different woodland types in *Ribeira dos Covões*. This may be due to different  
446 characteristics of the three types offsetting each other. Thus the larger scrub cover of the  
447 sparse eucalypt stand, which extended above throughfall gauges, may be the reason for  
448 ~~its~~ the slightly lower throughfall ([87%](#)) than ~~that recorded~~ in the dense eucalypt plantation  
449 (~~87 and 92%, respectively~~), with its limited underbrush cover (Table 1). ~~However, since~~ [As](#)  
450 throughfall measurements were made ~30 cm above the soil surface, [however, actual](#)  
451 interception by scrub less than 30 cm high would be missed and actual throughfall would  
452 be smaller than the values recorded.

453 ~~In Ribeira dos Covões the indicative throughfall percentages were generally in accordance~~  
454 ~~with or higher than those reported in literature dealing with similar woodland stands.~~ In

455 eucalypt plantations in *Ribeira dos Covões*, ~~the~~ median throughfall ~~of was~~ 92%, ~~at the~~  
456 ~~higher end similar to of the range of higher throughfall~~ values (58-92%) reported by  
457 Valente et al. (1997) ~~under for~~ *Eucalyptus globulus* Labill. stands elsewhere in Portugal (58-  
458 92%), ~~but and~~ higher than the values (85-88%) ~~for the same species~~ reviewed by Llorens  
459 and Domingo (2007). ~~under E. globulus (85-88%)~~. In shrubs and bushes (the dominant land  
460 cover under sparse eucalypt stand in the study catchment), a mean throughfall of about 49%  
461 has been reported (Llorens and Domingo, 2007). Despite, to the authors' knowledge, no  
462 throughfall measurements having been previously undertaken in *Q. robur*, *Q. faginea* or *Q.*  
463 *suber* (the forest species found in the oak stand within the catchment), the results from  
464 *Ribeira dos Covões* (median of 92%) are higher than those reported for *Q. cerris* L. (85-  
465 89%), *Q. pyrenaica*, (83-86%), *Q. coccifera* (55%) and *Q. ilex* (60-78%) (Llorens and  
466 Domingo, 2007).

467 ~~The relationships found between Throughfall was found to be affected by and~~ rainfall  
468 amount and intensity ~~tallies with findings as reported in of~~ previous studies (e.g. Gash,  
469 1979; Ferreira, 1996; Shachnovich et al., 2008; André et al., 2011). Smaller rainstorms (<  
470 3.7mm) could have been fully or ~~mostly partly~~ intercepted by vegetation (<3.7 mm), but  
471 with increasing storm rainfall and wet antecedent conditions, canopy storage exceedance  
472 leads to enhanced ~~percentage~~ throughfall ~~values~~, as reported elsewhere (Gash, 1979;  
473 Crockford and Richardson, 2000; Eisenbies et al., 2007; Bathurst et al., 2011). This may  
474 explain the ~~very high higher~~ throughfall in wetter ~~measurement~~ periods, ~~as well as the~~  
475 ~~higher results such as in the period~~ 2<sup>nd</sup> April 2011 - 5<sup>th</sup> March 2012, ~~than 2<sup>nd</sup> April 2011 -~~  
476 ~~5<sup>th</sup> March 2012~~, which included ~~d~~ some large rainstorm events.

477



## 478 5.1.2 Hydrophobicity

479 In *Ribeira dos Covões*, soil hydrophobicity was high and resistant to breakdown in eucalypt  
480 stands (particularly in the dense plantation), as widely reported previously (e.g. Doerr et al.,  
481 1996; Ferreira et al., 2000; Keizer et al., 2005; Keizer et al., 2008; Santos et al., 2013). In  
482 *Ribeira dos Covões*, however, hydrophobicity disappeared after 113 mm rain (period 11),  
483 whereas Ferreira et al. (2000) found hydrophobicity persisted after 200 mm rainfall in an  
484 area of schist soils farther north in Portugal. ~~Nevertheless, t~~The recorded increase in spatial  
485 extent (frequency)-the-extension and severity of hydrophobicity under eucalypt stands with  
486 soil depth, and the greater temporal variability at the soil surface than below it, ~~is in~~  
487 accord~~sance~~ with the findings of Keizer et al. (2005) for similar plantations in the coastal  
488 zone of central Portugal. The increase in hydrophobicity with soil depth, however, contrasts  
489 with the findings of Santos et al. (2013) in similar plantations but on schist soils in  
490 Portugal. Two possible reasons for the increase with depth are: (1) hydrophobic exudates  
491 being leached and precipitated in the subsoil during storm events, as reported by Doerr et  
492 al. (2000); and (2) hydrophobic conditions at depth being enhanced by greater preferential  
493 flow and less water infiltrating permeating into matrix soil at depth than at the soil surface.

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

499 The recorded differences in hydrophobicity severity and persistence between woodland  
500 types in *Ribeira dos Covões* (dense eucalypt > sparse eucalypt > oak) may in part be linked

501 to vegetation type and density, but could also be linked to soil texture differences.  
502 Hydrophobicity is more frequently associated with coarse- than fine-textured soils  
503 (DeBano, 1991; Cerdà and Doerr, 2007; Martínez-Zavala and Jordán-López, 2009) and can  
504 be reduced by small increases in clay content, depending on the clay type (McKissock et  
505 al., 2000). This could enhance the hydrophobicity on the sandier eucalypt locations on  
506 sandstone compared with the loamy oak woodland sites on limestone in the Ribeira dos  
507 Covões catchment.

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

515

### 516 **5.1.3 Soil moisture content**

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

524 | ~~opposed to 16-26° and 26-28° in dense and sparse eucalypt plots~~), as ~~found~~-reported  
525 | elsewhere by Zhu and Lin (2011); (3) the lower position of oak plots on the hillslope (Table  
526 | 1), leading to more effective moisture accumulation and retention than upslope (Kim, 2009;  
527 | Ridolfi et al., 2003); and (4) the presence of a few relict stone walls in the oak woodland  
528 | which may have increased water retention, as ~~found~~-recorded elsewhere by Yang et al.  
529 | (2012).

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

541 | ~~In addition to differences in soil properties and terrain characteristics,~~ The higher soil  
542 | moisture recorded under oak than eucalypt ~~sites~~ could also be linked to factors driven by  
543 | vegetation, such as transpiration and hydrophobicity (less intense and less frequent in oak  
544 | woodland soil). Daily transpiration from a mature *Eucalyptus globulus* Labill. stand in  
545 | Portugal varied between 0.5 and 3.6 mm day<sup>-1</sup> during a spring-summer period (David et al.,  
546 | 1997), although~~and~~ in south-eastern Australia, Forrester et al. (2010) reported transpiration

547 rates in eucalyptus plantations varying from 0.4 mm day<sup>-1</sup> in two-year-old stands at age 2-  
548 years to 1.6–1.9 mm day<sup>-1</sup> in stands aged 5–7 years. Lower transpiration rates of 1.3 mm  
549 day<sup>-1</sup> (464 mm a<sup>-1</sup>-) and 1.2 mm day<sup>-1</sup> 4(453 mm a<sup>-1</sup> ~~(1.3 and 1.2 mm day<sup>-1</sup>)~~) were reported  
550 for *Quercus ilex* L., in Catalonia, NE Spain, in valley and ridge-top locations, respectively  
551 (Sala and Tenhunen, 1996).

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

561 Surface soil moisture content appears to be strongly associated with hydrophobicity pattern.  
562 Generally, soil moisture was low when hydrophobicity was most severe and high when  
563 hydrophobicity was weak or absent. In *Ribeira dos Covões*, hydrophobicity was absent  
564 above soil moisture contents of 33%, 21% and 32% in dense eucalypt, sparse eucalypt and  
565 oak woodland, respectively (Figure 6). Similarly, extreme hydrophobicity was not recorded  
566 for soil moistures above 26%, 18% and 21%, respectively, reinforcing the view of the  
567 highly resilient nature of hydrophobicity in dense eucalypt plantations. Differences in the  
568 critical moisture content for the existence of hydrophobicity between woodland types may  
569 be linked to variations in soil texture (Doerr et al., 2000) and soil organic matter (Tumer et

570 al., 2005; Jordán et al., 2013), where the latter may be linked to species of trees and  
571 understorey vegetation. Previous studies have reported hydrophobicity for soil moisture  
572 contents of up to 22% in sandy loam soils (Doerr and Thomas, 2000), and as high as 38%  
573 in clayey soils (Dekker and Ritsema, 1994). Under eucalypt plantations in central Portugal,  
574 Santos et al. (2013) reported the dominance of strong and extreme hydrophobicity in schist  
575 soils when soil moisture content was below 14%, which is lower than for the [sandstone and](#)  
576 [limestone findings in Ribeira dos Covões findings](#).

577

#### 578 **5.1.4 Overland flow**

579 Runoff plots installed in *Ribeira dos Covões* recorded very low overland flow coefficients  
580 (<3%) in all the woodland [typesites](#). Generally, vegetation enhances infiltration,  
581 particularly in tree stands because of their comparatively deep root systems (Calvo-Cases et  
582 al., 2003; Hümann et al., 2011; Komatsu et al., 2011). Nevertheless, the underlying bedrock  
583 can also have an important effect on slope hydrology, particularly influencing infiltration  
584 and overland flow (Hattanji and Onda, 2004; Zhang and Hiscock, 2010). Generally, coarse-  
585 textured soils associated with sandstone are usually highly permeable, allowing water to  
586 drain freely. High permeability of limestone soils has been also widely reported in areas of  
587 Mediterranean climate (e.g. Calvo-Cases et al., 2003; Cerdà, 1997). Although bedrock  
588 differences in the study catchment may mask the influence of woodland type, significant  
589 overland flow differences were found between dense and sparse eucalyptus despite both  
590 being on sandstone, and no significant overland flow difference was identified between  
591 sparse eucalypt and oak stands despite the latter overlying limestone. Spatiotemporal  
592 variation in overland flow pattern between woodland types is thought instead to be a

593 consequence of hydrophobicity differences, since no significant throughfall difference was  
594 found between woodland stands, and soil moisture was higher in oak soils, where overland  
595 flow was lower.

596 In storm events following dry weather, the most likely cause of overland flow seemed to be  
597 infiltration-excess caused by hydrophobic soils, as suggested by previous surveys of point-  
598 scale hydrological soil properties in the catchment by (Ferreira et al. (2015)). Thus the  
599 greater severity and persistence of hydrophobicity in the dense eucalypt plantation are  
600 considered to be the reasons for its greater overland flow percentages, especially in larger  
601 rainstorms following dry antecedent conditions. In the sparse eucalypt stand, the less severe  
602 and patchier hydrophobicity also broke down more easily as a result of rainfall (see section  
603 4.2), thereby explaining the lower overland flow than in the dense eucalypt plantations.  
604 Nevertheless, smaller rainfall events (3.7 mm and 9.5 mm in period 23 and 25) failed to  
605 break down soil hydrophobicity in the sparse eucalyptus (Figure 3), which may explain the  
606 higher percentage overland recorded in those periods (Figure 6). In oak woodland, the low  
607 or moderate hydrophobicity and its much patchier nature would explain why infiltration-  
608 excess overland flow responses were very small even after prolonged dry weather.  
609 Differences in the breakdown resistance of hydrophobic properties may also be the reason  
610 for a stronger correlation between overland flow and rainfall in dense eucalypt plantation  
611 than in the other woodland types (see section 4.4).

612 Even under extreme hydrophobic conditions, however, overland flow was minor. Thus, the  
613 maximum average runoff coefficient at the dense eucalypt plots never exceeded 2.2%. This  
614 value is lower than the maximum of 10% measured in similar experimental plots in  
615 eucalypt stands in north-central Portugal following a long dry season, though for schist

616 soils (Ferreira et al., 2000). The low overland flow under extreme hydrophobicity suggests  
617 the role of water sinks within the woodland soils. Given the relatively low soil moisture  
618 content ~~of~~ hydrophobic soils, infiltration would seem to occur: (1) in hydrophilic soil  
619 patches, linked to a discontinuous hydrophobic layer, particularly under oak and sparse  
620 eucalypt stands (Figure 3); and (2) via preferential flow routes provided by cracks and root  
621 holes (Urbanek et al., 2015), although stones in sufficient quantities may also promote  
622 infiltration (Urbanek and Shakesby, 2009). Several authors have reported the relevance of  
623 preferential flow patterns for water infiltration in hydrophobic soils (DeBano, 2000; Doerr  
624 et al., 2000; Buczo et al., 2006). In hydrophobic sandy and sandy loam soils elsewhere,  
625 >80% (Ritsema et al., 1997) and 86-99% (Tsukamoto and Ohta, 1988) of water movement  
626 has been attributed to preferential flow.

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

633 In wet conditions, particularly in the dense eucalypt plots, it was unclear whether ~~overland~~  
634 flow (albeit much lower in percentage terms) was promoted by hydrophobicity-linked  
635 infiltration-excess ~~and/or~~ saturation-excess mechanisms. The persistence of subsurface  
636 hydrophobicity, in combination with a thin hydrophilic soil layer, may prevent downward  
637 water flux through the soil matrix (Doerr et al., 2000). Any infiltrated water would tend to  
638 pond above the hydrophobic layer leading to surface soil moisture build-up and possible

639 saturation (Doerr et al., 2000; Calvo-Cases et al., 2003). Under these conditions, ponded  
640 water in the surface saturated layer may be diverted laterally as throughflow unless  
641 encountering a vertical preferential flow path, allowing it to reach soil at greater depth and  
642 perhaps enter the underlying rock.

643 During the wettest conditions, overland flow appears to be generated by saturation-excess  
644 in the sparse eucalypt and, particularly, oak woodland types, as the soils were hydrophilic  
645 rather than hydrophobic. In the sparse eucalypt stand, generation of saturation overland  
646 flow may also have been favoured by the greater bulk density and clay content of its soil  
647 (Table 1) and its steeper slopes (26-28°), as found elsewhere by Neris et al. (2013).

648 | Theoretically Ssaturation overland flow ~~should be~~ ~~was~~ greatest in large rainfall events, when  
649 water detention by the surface micro-topography is exceeded leading to a greater downhill  
650 flux connectivity to develop (Yang et al., 2012). Surface topography may also enhance  
651 overland flow connectivity via local rills. Thus it was observed that during this study a rill  
652 developed on plot SE3 creating a concentrated surface path for overland flow, which may  
653 account for the significantly greater overland flow in that plot compared with in plots SE1  
654 and SE2 (see section 4.4).

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



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

674 In *Ribeira dos Covões*, the fact that overland flow after clear-felling was not higher than  
675 2.3% may be due to the thick ground cover of leaves, bark and small branches left in the  
676 harvested plot DE1, which would have enhanced water retention capacity and reduced any  
677 reduction in infiltration capacity due to splash effects. The enhancement of overland flow in  
678 DE1 was quickly reduced, first because of low rainfall in spring and summer and secondly  
679 | ~~with~~ due to rapid regeneration of vegetation after September 2012, in response to the onset  
680 | of the rainy late autumn-winter season. The timing of clear-felling may be a determining  
681 factor in overland flow impact, since felling performed during spring (rather than in late  
682 summer or autumn) allows vegetation to regenerate before autumn rains, minimizing  
683 overland flow impacts.

684

## 685 5.2 Implications for catchment streamflow and peri-urban catchment planning

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

696 | ~~The overland flow measurements undertaken in this study were conducted at a plot scale.~~  
697 | Overland flow responses, however, tend to diminish with increasing contributing area (van  
698 | de Giesen et al., 2000, 2005; Ferreira et al., 2011; Chamizo et al., 2012). Based on  
699 | measurements of soil hydrological properties at point-scale, Ferreira et al. (2015) suggested  
700 | that woodland areas in *Ribeira dos Covões* could be an important source of overland flow  
701 | in storm events during and immediately following during the summer dry seasons and other  
702 | prolonged dry periods. ~~Nevertheless, The very low runoff coefficients of the current plot-~~  
703 | ~~scale results in the same catchment regarding to the same study site showed very low runoff~~  
704 | ~~coefficients. This Tdemonstrates that the inverse relationship between overland flow and~~  
705 | ~~contributing areadecline~~ can be marked even with relatively small changes in area. This  
706 | tallies with the findings of ~~For example,~~ van de Giesen et al. (2005), who recorded a  
707 | decrease of 40–75% in overland flow from short (1.25 m) to long plots (12 m). On the

708 other hand, Mounirou et al. (2012) reported similar runoff amounts from 50 and 150 m<sup>2</sup>  
709 plots, though both were significantly lower than the smallest plot (1 m<sup>2</sup>) used. In an  
710 experimental study, Chamizo et al. (2012) found an optimal plot length of 20 m to  
711 determine runoff and sediment export rates representative of a catchment. At a much larger  
712 spatial scale, Cerdan et al. (2004), ~~in turn, observed recorded~~ a strong decrease in mean  
713 runoff coefficients with increasing area in studies performed at larger scales: three times  
714 lower for 90 ha than 450 m<sup>2</sup>, and ten times for 1100 ha than 90 ha.

715 Decreasing overland flow with increasing slope length is usually explained with greater  
716 opportunity for water infiltration on long than on short slopes (van de Giesen et al., 2005).  
717 It has also been attributed to increased soil heterogeneity with area, in terms of greater  
718 spatial variability in soil infiltration capacity (Cerdan et al., 2004; Mounirou et al., 2012),  
719 wettable patches and macropores, which can act as sinks for water (Calvo-Cases et al.,  
720 2003; Güntner and Bronstert, 2004; Nasta et al., 2009), as well as the temporal dynamics of  
721 the rainfall–runoff events (van de Giesen et al., 2005). Some authors have argued that  
722 spatial variability only has a scale-related effect on total runoff during relatively short  
723 rainfall events (van de Giesen et al., 2005; Mounirou et al., 2012). In *Ribeira dos Covões*,  
724 considering the small amounts of overland flow generated under woodland land-use even  
725 for relatively small runoff plots, it can be concluded that the generation in woodland areas  
726 of sufficiently continuous overland flow able to reach valley floors and channels would be  
727 rare. It would also suggest that patches of all three types of woodland could act as sinks for  
728 overland flow generated on upslope impervious urban surfaces.

729 ~~Although the minor overland flow measured in the study catchment supports the protective~~  
730 ~~role of forest land use during storm events,~~ The question remains, however, about overland

731 flow responses in rainfall events more extreme than those recorded in the two-year study.  
732 ~~†~~The highest daily rainfall recorded in the monitoring period was only 48 mm, which is less  
733 than a 2-year return period event (Brandão et al., 2001). On 25<sup>th</sup> October 2006, however,  
734 ~~hourly and~~following a period of very wet antecedent weather, a daily rainfall of 102 mm  
735 was recorded at Bencanta-Coimbra with a maximum hourly intensity of reached 565 mm  
736 ~~and 102 mm, respectively,~~ leading to major flooding of the Ribeira dos Covões.  
737 According to Brandão et al. (2001), daily rainfall events of 94 mm and 112 mm at Coimbra  
738 have return periods of 10- and 50-years, respectively. Since †The contribution from  
739 woodland areas to the 2006 flood is unknown and, †Overland flow responses in more  
740 ~~extreme events~~ can only be surmised. As the 25<sup>th</sup> October rainstorm followed a prolonged  
741 period of wet weather, it is highly likely that even in the dense eucalyptus the soil would  
742 have been largely hydrophilic and any overland flow generated in all three woodland types  
743 would probably have been saturation-excess in type. It is clearly possible that in such an  
744 extreme events the percentage saturation overland flow generated from all three woodland  
745 areas would have † been much greater than the maxima of <3-% recorded in the current  
746 study. Also a greater proportion and will also more readily be would have been transferred  
747 to downslope areas, since surface water retention capacities provided by litter and micro-  
748 topographic concavities would have † been exceeded. ~~Thus, s~~Although some studies have  
749 emphasized the limited storage capacity of forested terrain during larger storms and its  
750 minor role in flood protection (Bathurst et al., 2011; Eisenbies et al., 2007), it is considered  
751 that the high infiltration capacities of the soils of the catchment when hydrophilic (Ferreira  
752 et al., 2015) and the high storage capacities of the comparatively deep (>3m) sandstone  
753 soils of the dense and sparse eucalyptus sites would have limited the overland flow  
754 contribution from the eucalyptus woodland areas and retained some sink role for urban

755 runoff, with really high percentages of overland flow restricted to the oak woodland areas  
756 with their shallow, easily saturated soils. It is arguable, however, that the overland flow  
757 contribution from the dense eucalypt areas would have been much higher if an extreme  
758 storm of the magnitude of the 25<sup>th</sup> October 2006 event had occurred after dry antecedent  
759 weather when the dense eucalyptus soil would have been highly hydrophobic rather than  
760 hydrophilic. Clearly the timing of extreme events in relation to woodland -and soil types in  
761 a peri-urban catchment is of crucial significance to the size of overland flow responses and  
762 degree of downstream flooding.

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

772

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

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

782 On 25<sup>th</sup> October 2006, a rainfall event at Coimbra Bencanta of 102 mm after a long dry  
783 summer, led to a flash flood in *Ribeira dos Covões* catchment. According to Brandão et al.  
784 (2001), daily rainfall events of 94 mm and 112 mm at Coimbra have return periods of 10-  
785 and 50 years, respectively. Although the contribution from woodland areas to this flood is  
786 unknown, based on overland flow measurements performed under local woodland, dense  
787 eucalypt plantations could have some contribution to this flood, whereas sparse eucalypt  
788 and oak sites could provide upstream overland flow sinks.

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

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

820 ~~K~~nowledge of the impact of woodland areas, and particularly of woodland type on  
821 temporal overland flow dynamics should be taken into consideration in integrated planning  
822 and management of catchments undergoing urban development, particularly as regards  
823 planning the type and distribution of woodland patches and the delivery of urban surface

824 | runoff into these patches. Further investigation should be carried out in order to improve  
825 | understanding of the appropriate sizes and locations of distinct woodland areas within peri-  
826 | urban catchments, in order to minimize the hydrologic impacts of urbanization and protect  
827 | downslope urban cores from flood hazard.

828

## 829 | **6 Conclusions**

830 | In the peri-urban catchment of *Ribeira dos Covões* in central Portugal, —three distinct  
831 | woodland types on sandstone and limestone produced overland flow representing less than  
832 | 3% of the incident rainfall, based on measurements performed on small (16 m<sup>2</sup>) plots over  
833 | 2--years of monitoring. Plots on a managed dense eucalypt stand generated significantly 2.5  
834 | times more~~higher~~ overland flow than plots on sparse eucalypt or oak woodland on  
835 | abandoned peri-urban land, ~~which differed only slightly. Although the underlying bedrock~~  
836 | ~~can also influence hydrological processes, woodland type appears to be far more important,~~  
837 | ~~given the differences in soil hydrological properties and overland flow generation recorded~~  
838 | ~~on dense and sparse eucalypt stands, as they are both located on sandstone.~~

839 | In dry conditions, hydrophobicity-linked infiltration-excess overland flow was the  
840 | dominant means of downslope water movement. This process was particularly important in  
841 | dense eucalypt plantations, where hydrophobicity was more extreme, spatially contiguous  
842 | and resistant to breakdown with rainfall than was the case in the other two woodland types.  
843 | Under hydrophobic conditions at the dense eucalyptus sites, overland flow amount strongly  
844 | increased with rainfall amount and intensity, but median and individual plot overland flow  
845 | coefficients attained maxima of did not exceed 2.2% and 2.7%, respectively. In contrast, in  
846 | the sparse eucalypt plots, their moderate hydrophobicity after dry periods was easily broken



847 down, and percentage overland flow was greatest (albeit  $\leq 0.5\%$ ) in smaller rainfall events  
848 (~~overland flow coefficient  $\leq 0.5\%$~~ ), when the soil failed to become ~~was not rendered~~  
849 wettable within the event. The weak hydrophobic properties observed in oak woodland  
850 plots led to a maximum overland flow coefficient of only 0.4% in storms following dry  
851 antecedent weather, and median plot values of 0.3% for storms during the dry season.

852 In periods of wet weather, however, saturation overland flow occurred most readily in oak  
853 woodland followed by sparse eucalypt stands. Relatively high soil moisture contents  
854 maintained throughout wet periods enhanced saturation overland flow ~~by saturation~~, so that  
855 plot runoff coefficients reached 1.27% and 2.2% on the sparse eucalypt and oak woodland  
856 plotsites, respectively. ~~On~~ At the latter, saturation was favoured by the shallow soil  
857 overlying limestone, its loamy texture and subsurface lateral flow, whereas in the sparse  
858 eucalypt stand, saturation was favoured by the high bulk density and clayey nature of the  
859 soil. In both woodland types, overland flow strongly increased with rainfall amount and soil  
860 moisture. In contrast, in the dense eucalypt plantation, median overland flow ~~never~~ did not  
861 never exceeded 1.0% of rainfall in periods of wet weather.

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

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

886

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897

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Table 2 changes marked  
[Click here to download Table: Table2 Marked.docx](#)

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

	Throughfall (mm)	Hydrophobicity			Soil moisture (%)	Overland flow (mm)
		0-2cm	2-5cm	5-10cm		
Rainfall amount (mm)	0.83**	-0.31**	-0.29**	-0.30**	0.25**	0.51**
I <sub>30</sub> (mm h <sup>-1</sup> )	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 <sup>-3</sup> )	-	-0.06	-0.05	-0.07	-0.21**	-0.12**

Slope (°)	0.09	0.07	0.014**	0.13*	-0.32**	0.02
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1        **Differences in overland flow, hydrophobicity and soil moisture dynamics between**  
2                    **Mediterranean woodland types in a peri-urban catchment in Portugal**

3

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20

## 21 **Abstract**

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

45

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

48

## 49 **1. Introduction**

50 Forest covers 31% of the world's land surface (FAO, 2010) and 35% of mainland Portugal  
51 (ICNF, 2013). Globally forest cover has increased in recent decades as a result of greater  
52 demand for timber and environmental concerns (e.g. Robinson et al., 2003). However, in  
53 peri-urban catchments located in previously forested terrain, forest cover has decreased  
54 where urbanization has led to progressive deforestation and forest fragmentation (Nowak,  
55 2006) and remaining woodland can often change in character because of altered or  
56 abandoned management.

57 Forest hydrology has been widely documented, particularly with respect to some  
58 hydrological processes. Interception has been measured and modelled for many forest  
59 stands, indicating differences linked to distinct canopy architectures and woody matter and  
60 leaf characteristics and biomass (Muzylo et al., 2009; Rao et al., 2011). As a result of these  
61 factors (and climatic factors, notably rainstorm size distribution), throughfall varies greatly  
62 between forests, typically from 65 to 90% of precipitation, with stemflow generally varying  
63 from zero to 15 % (Herwitz and Levia, 1997; Crockford and Richardson, 2000; Wei et al.,  
64 2005). Differences in these processes can affect soil moisture distribution (Savva et al.,  
65 2013; He et al., 2014) and overland flow generation. Partly because overland flow is often  
66 considered a minor component of forest hydrology (Eisenbies et al., 2007; Gomi et al.,

67 2008), few studies have focused on differences in overland flow between different forest  
68 types, and in particular between unmanaged, often abandoned woodland types affected by  
69 peri-urbanization process and pre-existing managed forest plantations.

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

87 Although it is widely accepted that forests regulate water yield and reduce the size of most  
88 streamflow responses to rainfall because the high permeability of their soils (Eisenbies et  
89 al., 2007; Bathurst et al., 2011), the role of forest areas in flood protection in extreme

90 rainfall events has been hotly debated. Some have argued that interception and higher soil  
91 moisture deficits (of deeper, more porous and drier soils) under forest should reduce floods  
92 by removing a proportion of the storm rainfall (e.g. Bathurst et al., 2011), whereas others  
93 have argued that such water retention by forest is minimal in the extreme rainfall events  
94 that are responsible for floods (Eisenbies et al., 2007; Hümann et al, 2011; Komatsu et al.,  
95 2011),

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

106 This paper investigates the influence of three different types of woodland occurring within  
107 a peri-urban mosaic on overland flow generation in the *Ribeira dos Covões* catchment in an  
108 area of Mediterranean climate in central Portugal. Two of the woodland types investigated  
109 ((i) sparse eucalyptus adjacent to eucalyptus plantations and (ii) oak woodland) have been  
110 strongly influenced by semi-abandonment of land with peri-urbanization, whereas the third  
111 comprises pre-existing managed dense eucalyptus. A previous investigation in the same  
112 catchment (Ferreira et al. (2015) assessed temporal changes in soil properties (soil matrix

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

128

## 129 **2. Study area**

130 The study was carried out in the peri-urban *Ribeira dos Covões* catchment (8°27'W,  
131 40°13'N), located 3km NW of Coimbra, the largest city in central Portugal. The catchment  
132 (Figure 1) is 6.2km<sup>2</sup> in area, is aligned S-N and ranges in altitude from 34 to 205 m a.s.l.  
133 The area has a Mediterranean climate, with a mean annual temperature of 15°C and an  
134 average annual rainfall of 892 mm over the period 1941-2000 recorded at Coimbra-  
135 Bencanta (national meteorological weather station 12G/02UG), sited 0.5 km north of the

136 study catchment. A dry and hot season occurs from June to August (8% of annual rainfall),  
137 whereas the rainiest period is from November to March (61% of annual rainfall). Rainfall  
138 events are mostly small, with 83% of daily rainfalls in 2001-13 at Coimbra-Bencanta being  
139 <10 mm. Annual maximum daily rainfalls in 2001-13 ranged from 20 mm to 102 mm. The  
140 catchment is underlain by sandstone (57%) and limestone (43%). Soils developed on  
141 sandstone are classified as Fluvisols and Podsoles, following the WRB (2006) classification,  
142 and are generally deep (>3 m), while the Leptic Cambisols found on limestone slopes are  
143 typically shallow (<0.4 m) (Pato, 2007).

144 The catchment has undergone profound land-use changes over the last five decades, mainly  
145 associated with urbanization and planting of eucalyptus for timber production. Between  
146 1958 and 2007, the urban area expanded from 6% to 32% and woodland expanded from  
147 44% to 64%, at the expense of a marked decrease in agricultural land from 48 to 4%. Since  
148 2007, further urbanization has occurred mainly through deforestation. Thus by 2012, the  
149 urban area had increased to 40%, while the increasingly fragmented woodland area had  
150 decreased to 53% (Figure 1).

151 Currently, the woodland area consists mainly of *Eucalyptus globulus* Labill. plantations  
152 (55%), but with some mixed stands of eucalypt and pine (29%), scrubland (15%) and relict  
153 oak woodland composed of *Quercus robur* L., *Q. faginea broteroi* and *Q. suber* L. trees  
154 (1%) (Figure 1). Generally, eucalypt plantations occur on sandstone, but some areas,  
155 abandoned following logging, are now covered by sparse eucalypt stands with a dense  
156 scrub understorey. On limestone, vegetated areas are largely covered by shrubs (e.g.  
157 *Pistacia lentiscus*, *Spartium junceum*, *Cistus crispus*, *Ulex jussiaei*), but with semi-natural  
158 oak stands. In the oak area, a number of stone walls have survived from an earlier

159 agricultural land-use, mainly olive plantations. Thus both the sparse eucalyptus and oak  
160 woodland types have been strongly influenced by semi-abandonment of land with peri-  
161 urbanization.

162

### 163 **3. Methodology**

#### 164 **3.1 Experimental design and measurements**

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

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



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

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

192 Hydrophobicity and soil moisture content were measured on undisturbed land adjacent to  
193 each plot. Soil hydrophobicity was assessed at 0-2 cm, 2-5 cm and 5-7 cm depths along two  
194 1-m transects at either side of each plot using the 'Molarity of an Ethanol Droplet test'  
195 (Doerr, 1998). Sets of fifteen droplets of increasing ethanol concentration were applied  
196 along each transect until infiltration of at least eight droplets of the same concentration  
197 occurred within 5 seconds. The results for each transect were classified according to the  
198 following five repellency ratings and associated ethanol concentrations: wettable (0%); low  
199 (1, 3 and 5%); moderate (8.5 and 13%); severe (18 and 24 %); and extreme (36 and >36 %)  
200 hydrophobicity. Gravimetric soil moisture content was determined in the laboratory by  
201 oven-drying at 105°C for 24h. On each measurement occasion, this was done using one  
202 composite soil sample per plot (0-5cm soil depth), which was obtained by mixing 10

203 samples collected randomly on undisturbed land around each plot. Gravimetric was  
204 converted into volumetric water content using the mean soil bulk density of each site,  
205 calculated from 11 random soil samples of 143 cm<sup>3</sup> volume collected near to each plot,  
206 using purpose-built soil ring samplers of 5 cm diameter and 7.3 cm length.

207 Overland flow, throughfall, hydrophobicity and soil moisture were measured on 61  
208 occasions at 1- to 2-week intervals (depending on previous rainfall) over the 2-years from  
209 9<sup>th</sup> February 2011 to 14<sup>th</sup> April 2013. In March 2012, part of the dense eucalypt site was  
210 clear-felled, destroying plot DE2 (where monitoring was abandoned) and affecting tree  
211 interception at plot DE1. Owing to vandalism and theft of equipment on several occasions  
212 after clear-felling, throughfall measurement at the dense eucalypt plot locations was also  
213 abandoned from mid-2012 onwards.

214

### 215 **3.2 Data analysis**

216 In view of the non-normal distribution of the overland flow, throughfall, soil moisture and  
217 hydrophobicity data, non-parametric statistical tests were used to assess differences in  
218 median values between the three woodland types and between plots of the same woodland  
219 type. The Kruskal–Wallis test was employed to test the significance ( $p < 0.05$ ) of the  
220 differences with woodland type in overland flow, throughfall, hydrophobicity and soil  
221 moisture, and their seasonal variations. The statistical significance of differences in  
222 medians between seasons/plots/stands was assessed using the Least Significant Difference  
223 (LSD) test. The Spearman correlation coefficient ( $r$ ) was used to assess whether significant  
224 associations ( $p < 0.05$  and  $p < 0.01$ ) existed between rainfall characteristics (1- to 2-weekly  
225 totals, maximum 30-min rainfall intensities ( $I_{30}$ ) and 30-day antecedent rainfall) and soil

226 hydrological properties (hydrophobicity and soil moisture), as well as overland flow. All  
227 statistical analyses were carried out using IBM SPSS Statistics 22 software.

228

## 229 **4. Results and Analysis**

### 230 **4.1 Rainfall**

231 Overall, rainfall over the 2-year monitoring period (totalling 1581.7 mm) was relatively  
232 low, with annual rainfalls in 2011 and 2012 being 18 and 38% respectively below the long-  
233 term (1941-2000) average of 892 mm. The 61 measurement periods differed markedly in  
234 total rainfall amount (1.8-113 mm) (Figure 2), number of rainfall days (2-12) and  
235 maximum 30-min rainfall intensity ( $I_{30}$ : 0.6-24.8 mm h<sup>-1</sup>), but none represented extreme  
236 rainfall events (all beneath 2-years Intensity-Duration-Frequency curves for Coimbra  
237 (Brandão et al., 2001). The seasonal pattern was typically Mediterranean, with distinctly  
238 lower rainfall in summer (4% of total rainfall fell in June to August) compared with 35% in  
239 autumn, 32% in winter and 28% in spring. Nevertheless, there was also a very dry period in  
240 winter 2011/12 from 21<sup>st</sup> December 2011 to 20<sup>th</sup> March 2012 (37 mm). In contrast,  
241 November 2011, January 2013 and March 2013 were wetter than the long-term 1941-2000  
242 averages (163 vs 111 mm, 166 vs 116 mm and 228 vs 87 mm, respectively). In total there  
243 were 333 days with rain during the 2-year monitoring period, with 47 daily falls exceeding  
244 10.0 mm, of which four exceeded 25.0 mm. The highest daily falls were 48.1 mm on 14<sup>th</sup>  
245 December 2012, 43.1 mm on 7<sup>th</sup> March 2013, 29.0 mm on 19<sup>th</sup> January 2013 and 26.8 mm  
246 on 2<sup>nd</sup> November 2011. These falls are well below 102 mm fall recorded on 25<sup>th</sup> October  
247 2006, which led to floods within the catchment.

248

## 249 **4.2 Throughfall**

250 Although, given the small number of gauges, assessments were only exploratory,  
251 throughfall for the period 2<sup>nd</sup> April 2011 to 5<sup>th</sup> March 2012 (periods 3-23), when  
252 measurements were carried out at all three woodland sites, was higher in dense eucalypt  
253 (92% of rainfall) than in sparse eucalypt (87%) and oak stands (82%) (Figure 2). For the 2-  
254 year period 2<sup>nd</sup> April 2011 to 14<sup>th</sup> April 2013 (periods 3-61), however, overall throughfall  
255 percentages were rather higher (97% and 92% of rainfall in the sparse eucalypt and oak  
256 stands respectively. In both periods, differences in percentage throughfall between  
257 woodland types were found to be not statistically significant ( $p>0.05$ ).

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

264

## 265 **4.2 Hydrophobicity**

266 In all soil layers, hydrophobicity was most severe and frequent in the dense eucalypt  
267 plantations, intermediate in the sparse eucalypt stand and least in the oak woodland  
268 ( $p<0.05$ ) (Figure 3). In the oak stand, hydrophobicity was absent on many measurement  
269 dates (69% of occasions at both 0-2 cm and 2-5 cm and 48% of occasions at 5-7 cm) and  
270 was largely of low or moderate severity when present. In this woodland type,

271 hydrophobicity was mainly transient in nature, being recorded in all the sampling sites only  
272 on 14%, 13% and 17% of monitoring occasions, at 0-2 cm, 2-5 cm and 5-7 cm depth,  
273 respectively. In the sparse eucalypt site, hydrophobicity showed the greatest spatial and  
274 temporal variation; hydrophilic conditions were dominant on 49%, 34% and 39% of the  
275 measurement dates, at 0-2 cm, 2-5 cm and 5-7 cm, respectively, but hydrophobicity was  
276 mostly moderate to severe when present. As in oak woodland, the sparse eucalypt stand  
277 showed a transient and patchy hydrophobic pattern, with widespread hydrophobicity  
278 recorded on just 26% of the 61 measurement occasions at 0-2 cm and 5-7 cm and on 24%  
279 of occasions at 2-5 cm depth. In contrast, in dense eucalypt plantations, hydrophilic  
280 conditions were only observed on 41%, 15% and 13% of occasions, at 0-2 cm, 2-5 cm and  
281 5-7 cm depth respectively, with severe to extreme hydrophobic properties being dominant  
282 and widespread on 53%, 55% and 70% respectively of occasions when hydrophobicity was  
283 present.

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

291 In dense eucalypt stands, hydrophobicity increased in frequency and severity with soil  
292 depth (differences between 0-2 cm and 5-10 cm layers,  $p < 0.05$ ). Also, more rainstorms  
293 were required to reduce hydrophobicity levels in deeper soil. Extreme hydrophobicity was

294 recorded on 18%, 13% and 30% of occasions respectively at 0-2 cm, 2-5 cm and 5-10 cm.  
295 A similar pattern with depth occurred at the sparse eucalypt site, despite lower  
296 hydrophobicity severity and coverage (extreme hydrophobicity was recorded on 8%, 13%  
297 and 15% of occasions, at 0-2 cm, 2-5 cm and 5-10 cm depth, respectively). In contrast to  
298 eucalypt sites, hydrophobicity did not vary significantly with soil depth in oak woodland  
299 ( $p>0.05$ ), although it showed a tendency to decrease in severity but increase in temporal  
300 frequency with soil depth (Figure 3).

301 Although hydrophobicity severity and spatial frequency varied with antecedent weather at  
302 all sites and at all depths in all woodland types, inverse relationships with storm rainfall and  
303 throughfall amount, although statistically significant ( $p<0.01$ ), are weak ( $r$  never exceeding  
304  $-0.31$ ) and are not statistically significant in the case of maximum rainfall intensity ( $p>0.05$ )  
305 (Table 2).

306

### 307 **4.3 Soil moisture content**

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

311 Soil moisture content increased significantly with preceding period rainfall amount and  
312 throughfall ( $p<0.01$ ), although relationships were not very strong (Table 2). It was  
313 substantially lower in summer than in other seasons ( $p<0.05$ ), with a similar median value  
314 (8%) for all woodland types. Soil moisture was much higher in autumn, winter and spring  
315 (24%, 25% and 21%, respectively), but with variations between years. During spring,

316 median soil moisture content was higher in 2013 (22%) than in both 2011 (16%) and 2012  
317 (11%) ( $p < 0.05$ ). In autumn, soil moisture was significantly higher in 2011 than in 2012  
318 (28% vs 17%) ( $p < 0.05$ ). In winter, median soil moisture reached highest values in 2013  
319 (26% compared with 19% in 2011 and 20% in 2012). Generally, higher soil moisture  
320 content was observed during autumn 2011 (median values of 27%, 33% and 27% for ED,  
321 EO and O, respectively), winter 2013 (median values of 23%, 24% and 36% for ED, EO  
322 and O, respectively) and spring 2013 (median values of 18%, 22% and 36% for ED, EO  
323 and O, respectively). Soil moisture content reached highest values of 37%, 32% and 49% in  
324 ED, EO and O in winter 2013, but the peak value of 47% in the EO site was attained in  
325 autumn 2011.

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

331

#### 332 **4.4 Overland flow**

333 The median plot values of overland flow amount in mm (above) and as a percentage of  
334 rainfall (below) for each woodland type in each of the 61 measurement periods is shown in  
335 Figure 5. Although overland flow was generated in most measurement periods (97, 92 and  
336 89% of occasions for dense eucalypt, sparse eucalypt and oak stands, respectively), median  
337 overland flow exceeded 1% of period rainfall on just 8, 4 and 3 occasions out of 61 for  
338 dense eucalypt, sparse eucalypt and oak sites, respectively, and never exceeded 3% (Figure

339 5). Overland flow amounts (median values for individual periods), were significantly  
340 higher in the dense eucalypt plantation than in the sparse eucalypt and oak stands ( $p < 0.05$ ,  
341 Kruskal-Wallis and LSD tests) and overland flow over the two-year period was over twice  
342 as high in dense eucalyptus (6.9 mm, 0.43%) than at the sparse eucalyptus (2.6 mm, 0.16%)  
343 and oak woodland (2.9 mm, 0.18%) plots. Differences in the temporal pattern of overland  
344 flow were also observed between woodland stands. Dense eucalypt plantation plots  
345 generated greater percentage overland flow (medians of up to 2.2%) in rainstorms occurring  
346 after dry antecedent weather (especially in late spring, summer and at the beginning of  
347 autumn), whereas in wet conditions, even in large events, it never exceeded 1.0 %. In the  
348 sparse eucalypt stand, median overland flow varied in contrary fashion over the year, with  
349 higher values in wet weather of autumn, winter and spring and lower values in storms  
350 following dry periods, particular in summer and early autumn. Thus the maximum recorded  
351 median runoff coefficient was only 0.4% in a measurement period after dry weather but  
352 1.3% after wet weather. In the dense eucalypt plantation, the highest percentage overland  
353 flow values were recorded in moderate rainfall events (4-23 mm and  $I_{30} = 3-16 \text{ mm h}^{-1}$ ),  
354 whereas in the sparse eucalypt stand highest percentage overland flow occurred in  
355 relatively small rainfall events (4-10 mm and  $I_{30} = 3-6 \text{ mm h}^{-1}$ ). Again, in contrast to the  
356 dense eucalypt plots, in oak woodland overland flow was mainly produced after the  
357 wettest antecedent weather and soil moisture conditions, attaining higher values mostly in  
358 larger rainfall events ( $> 10 \text{ mm}$ ) in winter and spring 2013, the wettest part of the 2-year  
359 study. In the oak woodland, however, even in the wettest periods, median runoff coefficient  
360 values of the three replicated plots never exceeded 0.6% and following dry weather both  
361 median and individual plot runoff coefficients never exceeded 0.4%.



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

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

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

384

## 385 5 Discussion

### 386 5.1 Temporal patterns of hydrological properties and woodland type

#### 387 5.1.1 Throughfall

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

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

407 reported for *Q. cerris* L. (85-89%), *Q. pyrenaica*, (83-86%), *Q. coccifera* (55%) and *Q. ilex*  
408 (60-78%) (Llorens and Domingo, 2007).

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

418

### 419 **5.1.2 Hydrophobicity**

420 In *Ribeira dos Covões*, soil hydrophobicity was high and resistant to breakdown in eucalypt  
421 stands (particularly in the dense plantation), as widely reported previously (e.g. Doerr et al.,  
422 1996; Ferreira et al., 2000; Keizer et al., 2005; Keizer et al., 2008; Santos et al., 2013). In  
423 *Ribeira dos Covões*, however, hydrophobicity disappeared after 113 mm rain (period 11),  
424 whereas Ferreira et al. (2000) found hydrophobicity persisted after 200 mm rainfall in an  
425 area of schist soils farther north in Portugal. The recorded increase in spatial extent  
426 (frequency) and severity of hydrophobicity under eucalypt stands with soil depth, and the  
427 greater temporal variability at the soil surface than below it, accords with the findings of  
428 Keizer et al. (2005) for similar plantations in the coastal zone of central Portugal. The  
429 increase in hydrophobicity with soil depth, however, contrasts with the findings of Santos

430 et al. (2013) in similar plantations but on schist soils in Portugal. Two possible reasons for  
431 the increase with depth are: (1) hydrophobic exudates being leached and precipitated in the  
432 subsoil during storm events, as reported by Doerr et al. (2000); and (2) hydrophobic  
433 conditions at depth being enhanced by greater preferential flow and less water infiltrating  
434 permeating into matrix soil at depth than at the soil surface.

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

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

449 The seasonal hydrophobicity pattern characterized by greater severity and spatial extent in  
450 dry periods, and lower under wet settings, has been widely reported elsewhere (Dekker and  
451 Ritsema, 1994; DeBano, 2000; Doerr et al., 2000; Ferreira et al., 2000; Keizer et al., 2005;  
452 Santos et al., 2013) and is clearly linked to the antecedent (including seasonal) rainfall

453 pattern. The significant inverse correlations found between hydrophobicity and antecedent  
454 rainfall were also recorded by Buczko et al. (2007), but not by Santos et al. (2013) for other  
455 eucalypt sites in Portugal.

456

### 457 **5.1.3 Soil moisture content**

458 The higher soil moisture content recorded under oak than in the two eucalypt stands may be  
459 associated with higher water retention by the finer-textured soil overlying limestone  
460 bedrock compared with the coarser sandstone soils of the eucalypt areas. The higher soil  
461 moisture content under oak, however, could also result from: (1) more effective ponding by  
462 underlying bedrock in the shallower soil (<0.4 m on limestone as opposed to >3 m in  
463 sandstone), as found elsewhere (Maeda et al., 2006; Hardie et al., 2012; Yang et al., 2012);  
464 (2) the lower slope angles of the oak woodland site (Table 1, as reported elsewhere by Zhu  
465 and Lin (2011); (3) the lower position of oak plots on the hillslope (Table 1), leading to  
466 more effective moisture accumulation and retention than upslope (Kim, 2009; Ridolfi et al.,  
467 2003); and (4) the presence of a few relict stone walls in the oak woodland which may have  
468 increased water retention, as recorded elsewhere by Yang et al. (2012).

469 In order to assess the importance of topography, particularly the slope and upslope areas  
470 that can contribute with overland flow, on soil moisture differences between woodland  
471 types, Topographic Wetness Index (TWI) was calculated for the catchment area, using the  
472 method described by Pei et al. (2010). Although in *Ribeira dos Covões* catchment TWI  
473 reaches 21, TWI values for the woodland plots do not exceed 5, highlighting the lower  
474 probability of saturation excess overland flow. Nevertheless, the differences in TWI values

475 between the sparse eucalyptus (1-2) dense eucalyptus (2-3) and oak woodland plots (4-5)  
476 may explain the greatest soil moisture content being measured at the oak woodland sites.

477 The higher soil moisture recorded under oak than eucalypt could also be linked to factors  
478 driven by vegetation, such as transpiration and hydrophobicity (less intense and less  
479 frequent in oak woodland soil). Daily transpiration from a mature *Eucalyptus globulus*  
480 Labill. stand in Portugal varied between 0.5 and 3.6 mm day<sup>-1</sup> during a spring-summer  
481 period (David et al., 1997), although in south-eastern Australia, Forrester et al. (2010)  
482 reported transpiration rates in eucalyptus plantations varying from 0.4 mm day<sup>-1</sup> in two-  
483 year-old stands to 1.6–1.9 mm day<sup>-1</sup> in stands aged 5–7 years. Lower transpiration rates of  
484 1.3 mm day<sup>-1</sup> (464 mm a<sup>-1</sup>) and 1.2 mm day<sup>-1</sup> (453 mm a<sup>-1</sup>) were reported for *Quercus ilex*  
485 L., in Catalonia, NE Spain, in valley and ridge-top locations, respectively (Sala and  
486 Tenhunen, 1996). In *Ribeira dos Covões*, the higher soil moisture content in oak than  
487 eucalypt stands, however, does not seem to result from greater water consumption by  
488 eucalypt trees, since no significant difference in soil moisture was found between dense and  
489 sparse eucalypt stands. Indeed the evapotranspiration rate of extensive scrub cover can be  
490 similar to that of eucalypt trees (Bellot et al., 2004; Hümann et al., 2011; Yang et al., 2012),  
491 which could account for the absence of significant soil moisture differences between the  
492 sparse and dense eucalypt stands. The high evapotranspiration provided by the scrub cover  
493 may also counterbalance the higher soil water retention expected at the sparse than dense  
494 eucalypt stands, due to higher silt and clay contents (Table 1).

495 Surface soil moisture content appears to be strongly associated with hydrophobicity pattern.  
496 Generally, soil moisture was low when hydrophobicity was most severe and high when  
497 hydrophobicity was weak or absent. In *Ribeira dos Covões*, hydrophobicity was absent

498 above soil moisture contents of 33%, 21% and 32% in dense eucalypt, sparse eucalypt and  
499 oak woodland, respectively (Figure 6). Similarly, extreme hydrophobicity was not recorded  
500 for soil moistures above 26%, 18% and 21%, respectively, reinforcing the view of the  
501 highly resilient nature of hydrophobicity in dense eucalypt plantations. Differences in the  
502 critical moisture content for the existence of hydrophobicity between woodland types may  
503 be linked to variations in soil texture (Doerr et al., 2000) and soil organic matter (Tumer et  
504 al., 2005; Jordán et al., 2013), where the latter may be linked to species of trees and  
505 understorey vegetation. Previous studies have reported hydrophobicity for soil moisture  
506 contents of up to 22% in sandy loam soils (Doerr and Thomas, 2000), and as high as 38%  
507 in clayey soils (Dekker and Ritsema, 1994). Under eucalypt plantations in central Portugal,  
508 Santos et al. (2013) reported the dominance of strong and extreme hydrophobicity in schist  
509 soils when soil moisture content was below 14%, which is lower than for the sandstone and  
510 limestone findings in *Ribeira dos Covões*.

511

#### 512 **5.1.4 Overland flow**

513 Runoff plots installed in *Ribeira dos Covões* recorded very low overland flow coefficients  
514 (<3%) in all the woodland types. Generally, vegetation enhances infiltration, particularly in  
515 tree stands because of their comparatively deep root systems (Calvo-Cases et al., 2003;  
516 Hümann et al., 2011; Komatsu et al., 2011). Nevertheless, the underlying bedrock can also  
517 have an important effect on slope hydrology, particularly influencing infiltration and  
518 overland flow (Hattanji and Onda, 2004; Zhang and Hiscock, 2010). Generally, coarse-  
519 textured soils associated with sandstone are usually highly permeable, allowing water to  
520 drain freely. High permeability of limestone soils has been also widely reported in areas of

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

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



544 for a stronger correlation between overland flow and rainfall in dense eucalypt plantation  
545 than in the other woodland types (see section 4.4).

546 Even under extreme hydrophobic conditions, however, overland flow was minor. Thus, the  
547 maximum average runoff coefficient at the dense eucalypt plots never exceeded 2.2%. This  
548 value is lower than the maximum of 10% measured in similar experimental plots in  
549 eucalypt stands in north-central Portugal following a long dry season, though for schist  
550 soils (Ferreira et al., 2000). The low overland flow under extreme hydrophobicity suggests  
551 the role of water sinks within the woodland soils. Given the relatively low soil moisture  
552 content of hydrophobic soils, infiltration would seem to occur: (1) in hydrophilic soil  
553 patches, linked to a discontinuous hydrophobic layer, particularly under oak and sparse  
554 eucalypt stands (Figure 3); and (2) via preferential flow routes provided by cracks and root  
555 holes (Urbanek et al., 2015), although stones in sufficient quantities may also promote  
556 infiltration (Urbanek and Shakesby, 2009). Several authors have reported the relevance of  
557 preferential flow patterns for water infiltration in hydrophobic soils (DeBano, 2000; Doerr  
558 et al., 2000; Buczo et al., 2006). In hydrophobic sandy and sandy loam soils elsewhere,  
559 >80% (Ritsema et al., 1997) and 86-99% (Tsukamoto and Ohta, 1988) of water movement  
560 has been attributed to preferential flow.

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

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

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

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

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

608 In *Ribeira dos Covões*, the fact that overland flow after clear-felling was not higher than  
609 2.3% may be due to the thick ground cover of leaves, bark and small branches left in the  
610 harvested plot DE1, which would have enhanced water retention capacity and reduced any  
611 reduction in infiltration capacity due to splash effects. The enhancement of overland flow in

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

618

## 619 **5.2 Implications for catchment streamflow and peri-urban catchment planning**

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

630 Overland flow responses, however, tend to diminish with increasing contributing area (van  
631 de Giesen et al., 2000, 2005; Ferreira et al., 2011; Chamizo et al., 2012). Based on  
632 measurements of soil hydrological properties at point-scale, Ferreira et al. (2015) suggested  
633 that woodland areas in *Ribeira dos Covões* could be an important source of overland flow  
634 in storm events during and immediately following the summer dry season and other

635 prolonged dry periods. The very low runoff coefficients of the current plot-scale results in  
636 the same catchment demonstrates that the inverse relationship between overland flow and  
637 contributing area can be marked even with relatively small changes in area. This tallies  
638 with the findings of van de Giesen et al. (2005), who recorded a decrease of 40–75% in  
639 overland flow from short (1.25 m) to long plots (12 m). On the other hand, Mounirou et al.  
640 (2012) reported similar runoff amounts from 50 and 150 m<sup>2</sup> plots, though both were  
641 significantly lower than the smallest plot (1 m<sup>2</sup>) used. In an experimental study, Chamizo et  
642 al. (2012) found an optimal plot length of 20 m to determine runoff and sediment export  
643 rates representative of a catchment. At a much larger spatial scale, Cerdan et al. (2004)  
644 recorded a strong decrease in mean runoff coefficients with increasing area in studies  
645 performed at larger scales: three times lower for 90 ha than 450 m<sup>2</sup>, and ten times for 1100  
646 ha than 90 ha.

647 Decreasing overland flow with increasing slope length is usually explained with greater  
648 opportunity for water infiltration on long than on short slopes (van de Giesen et al., 2005).  
649 It has also been attributed to increased soil heterogeneity with area, in terms of greater  
650 spatial variability in soil infiltration capacity (Cerdan et al., 2004; Mounirou et al., 2012),  
651 wettable patches and macropores, which can act as sinks for water (Calvo-Cases et al.,  
652 2003; Güntner and Bronstert, 2004; Nasta et al., 2009), as well as the temporal dynamics of  
653 the rainfall–runoff events (van de Giesen et al., 2005). Some authors have argued that  
654 spatial variability only has a scale-related effect on total runoff during relatively short  
655 rainfall events (van de Giesen et al., 2005; Mounirou et al., 2012). In *Ribeira dos Covões*,  
656 considering the small amounts of overland flow generated under woodland land-use even  
657 for relatively small runoff plots, it can be concluded that the generation in woodland areas  
658 of sufficiently continuous overland flow able to reach valley floors and channels would be

659 rare. It would also suggest that patches of all three types of woodland could act as sinks for  
660 overland flow generated on upslope impervious urban surfaces.

661 The question remains, however, about overland flow responses in rainfall events more  
662 extreme than those recorded in the two-year study. The highest daily rainfall recorded in the  
663 monitoring period was only 48 mm, which is less than a 2-year return period event  
664 (Brandão et al., 2001). On 25<sup>th</sup> October 2006, however, following a period of very wet  
665 antecedent weather, a daily rainfall of 102 mm was recorded at Bencanta-Coimbra with a  
666 maximum hourly intensity of 56 mm leading to major flooding of the *Ribeira dos Covões*.  
667 According to Brandão et al. (2001), daily rainfall events of 94 mm and 112 mm at Coimbra  
668 have return periods of 10- and 50-years, respectively. The contribution from woodland  
669 areas to the 2006 flood is unknown and can only be surmised. As the 25<sup>th</sup> October  
670 rainstorm followed a prolonged period of wet weather, it is highly likely that even in the  
671 dense eucalyptus the soil would have been largely hydrophilic and any overland flow  
672 generated in all three woodland types would probably have been saturation-excess in type.  
673 It is clearly possible that in such an extreme event the percentage saturation overland flow  
674 generated from all three woodland areas would have been much greater than the maxima of  
675 <3% recorded in the current study. Also a greater proportion would have been transferred  
676 to downslope areas, since surface water retention capacities provided by litter and micro-  
677 topographic concavities would have been exceeded. Although some studies have  
678 emphasized the limited storage capacity of forested terrain during larger storms and its  
679 minor role in flood protection (Bathurst et al., 2011; Eisenbies et al., 2007), it is considered  
680 that the high infiltration capacities of the soils of the catchment when hydrophilic (Ferreira  
681 et al., 2015) and the high storage capacities of the comparatively deep (>3m) sandstone  
682 soils of the dense and sparse eucalyptus sites would have limited the overland flow

683 contribution from the eucalyptus woodland areas and retained some sink role for urban  
684 runoff, with really high percentages of overland flow restricted to the oak woodland areas  
685 with their shallow, easily saturated soils. It is arguable, however, that the overland flow  
686 contribution from the dense eucalypt areas would have been much higher if an extreme  
687 storm of the magnitude of the 25<sup>th</sup> October 2006 event had occurred after dry antecedent  
688 weather when the dense eucalyptus soil would have been highly hydrophobic rather than  
689 hydrophilic. Clearly the timing of extreme events in relation to woodland and soil types in  
690 a peri-urban catchment is of crucial significance to the size of overland flow responses and  
691 degree of downstream flooding.

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

697 Woodland is the dominant land-use in *Ribeira dos Covões* catchment, followed by urban  
698 surfaces, which in some places interrupts woodland patches (Figure 1). The increase in  
699 impervious area and catchment discharge with additional urbanization in recent years is  
700 expected to continue given the future urban development already approved (Ferreira et al.,  
701 2013). The small amounts of overland flow generated in all three woodland types  
702 demonstrates that patches of woodland can provide potential sinks for overland flow  
703 generated from upslope impervious urban surfaces if they naturally or are directed to flow  
704 into such patches. The magnitude and effectiveness of such a sink role in a peri-urban  
705 catchment, will be affected (1) by the type of woodland, given the differences in overland

706 flow mechanisms and responses shown by this study, (2) their distribution within the  
707 catchment in relation to upslope urban surfaces and (3) the extent to which upslope urban  
708 runoff flows into them. It is argued here that knowledge of the impact of woodland areas,  
709 and particularly of woodland type on temporal overland flow dynamics should be taken  
710 into consideration in integrated planning and management of catchments undergoing urban  
711 development, particularly as regards planning the type and distribution of woodland patches  
712 and the delivery of urban surface runoff into these patches. Further investigation should be  
713 carried out in order to improve understanding of the appropriate sizes and locations of  
714 distinct woodland areas within peri-urban catchments, in order to minimize the hydrologic  
715 impacts of urbanization and protect downslope urban cores from flood hazard.

716

## 717 **6 Conclusions**

718 In the peri-urban catchment of *Ribeira dos Covões* in central Portugal, three distinct  
719 woodland types on sandstone and limestone produced overland flow representing less than  
720 3% of the incident rainfall, based on measurements performed on small (16 m<sup>2</sup>) plots over  
721 2-years of monitoring. Plots on a managed dense eucalypt stand generated significantly 2.5  
722 times more overland flow than plots on sparse eucalypt or oak woodland on abandoned  
723 peri-urban land.

724 In dry conditions, hydrophobicity-linked infiltration-excess overland flow was the  
725 dominant means of downslope water movement. This process was particularly important in  
726 dense eucalypt plantations, where hydrophobicity was more extreme, spatially contiguous  
727 and resistant to breakdown with rainfall than was the case in the other two woodland types.  
728 Under hydrophobic conditions at the dense eucalyptus sites, overland flow amount strongly



729 increased with rainfall amount and intensity, but median and individual plot overland flow  
730 coefficients attained maxima of 2.2% and 2.7%, respectively. In contrast, in the sparse  
731 eucalypt plots, their moderate hydrophobicity after dry periods was easily broken down,  
732 and percentage overland flow was greatest (albeit  $\leq 0.5\%$ ) in smaller rainfall events when  
733 the soil failed to become wettable within the event. The weak hydrophobic properties  
734 observed in oak woodland plots led to a maximum overland flow coefficient of only 0.4%  
735 in storms following dry antecedent weather, and median plot values of 0.3% for storms  
736 during the dry season.

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

747 Interception by the different woodland types was not significantly different, based on  
748 exploratory throughfall measurements performed. It is thought to have been important in  
749 reducing overland flow responses only during small rainfall events following antecedent  
750 dry weather, as throughfall was high (and interception was low) in percentage terms during  
751 large events and wet periods due to canopy saturation. In addition, surface roughness,

752 associated with the litter layer promoted water retention and decreased lateral flow  
753 connectivity.

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

770

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781

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1018 152, 361–374.

Figure 1

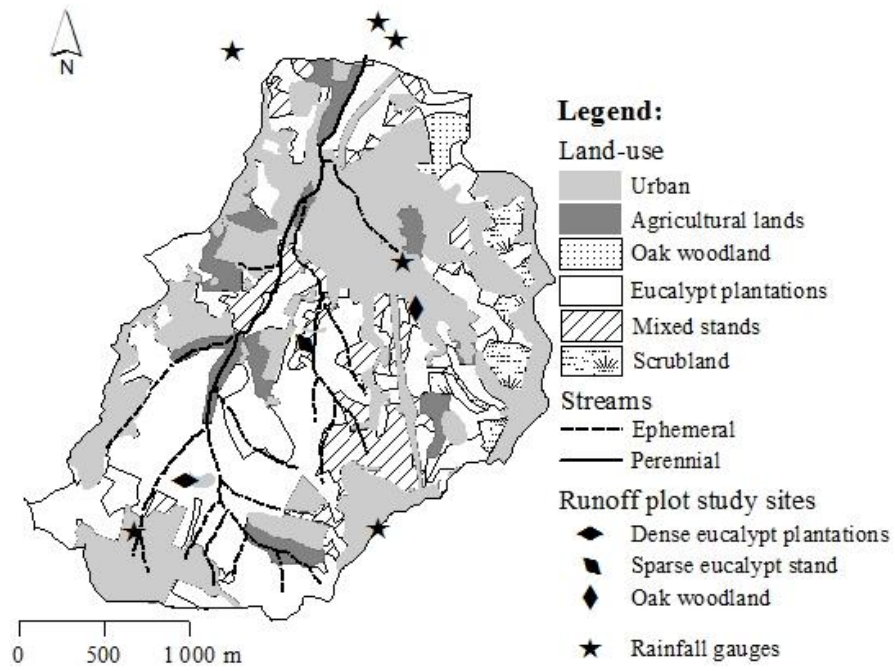


Figure 1 – Ribeira dos Covões catchment land-use and location of the study sites instrumented with runoff plots.

Figure 2

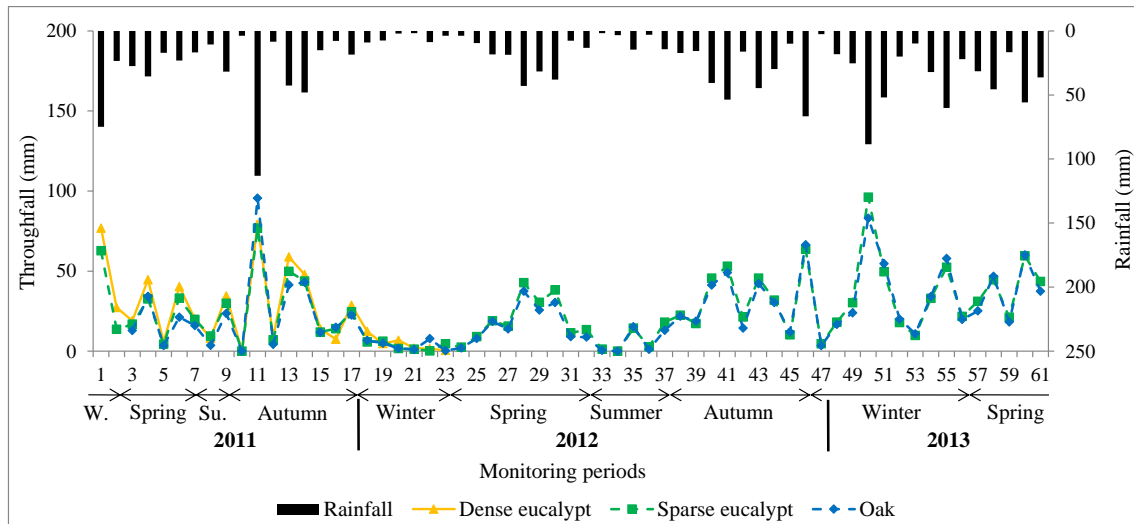


Figure 2 – Weighted average rainfall amount and median throughfall per woodland type, for the 61 measurement periods from 9<sup>th</sup> February 2011 to 14<sup>th</sup> April 2013. Throughfall results only until 5<sup>th</sup> March 2012 in dense eucalypt plantation due to collectors' theft.



Figure 3

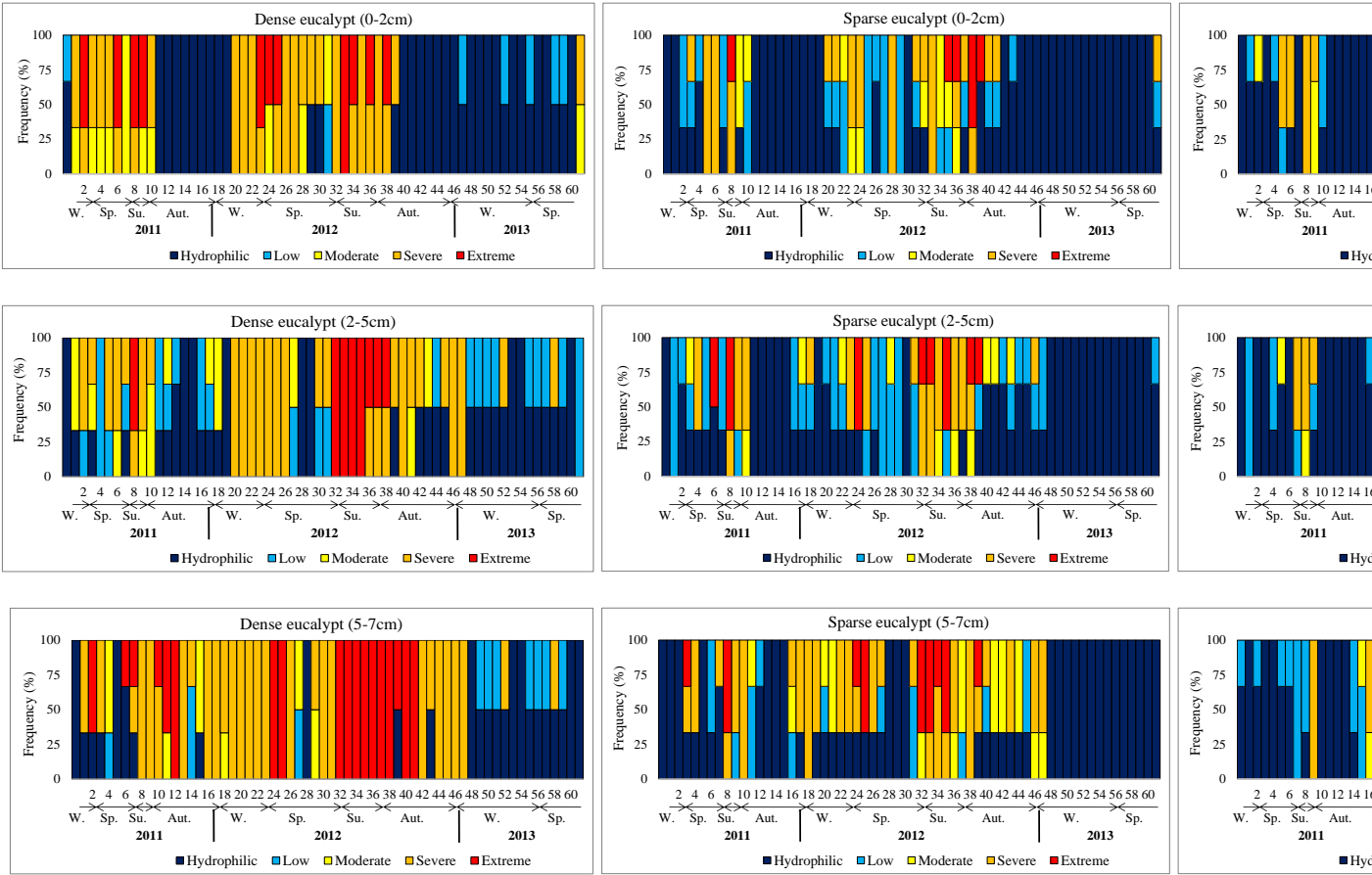


Figure 3 – Temporal variability of frequency distribution of hydrophobicity classes per woodland type and s for the 61 measurement periods from 9<sup>th</sup> February 2011 to 14<sup>th</sup> April 2013.



Figure 4

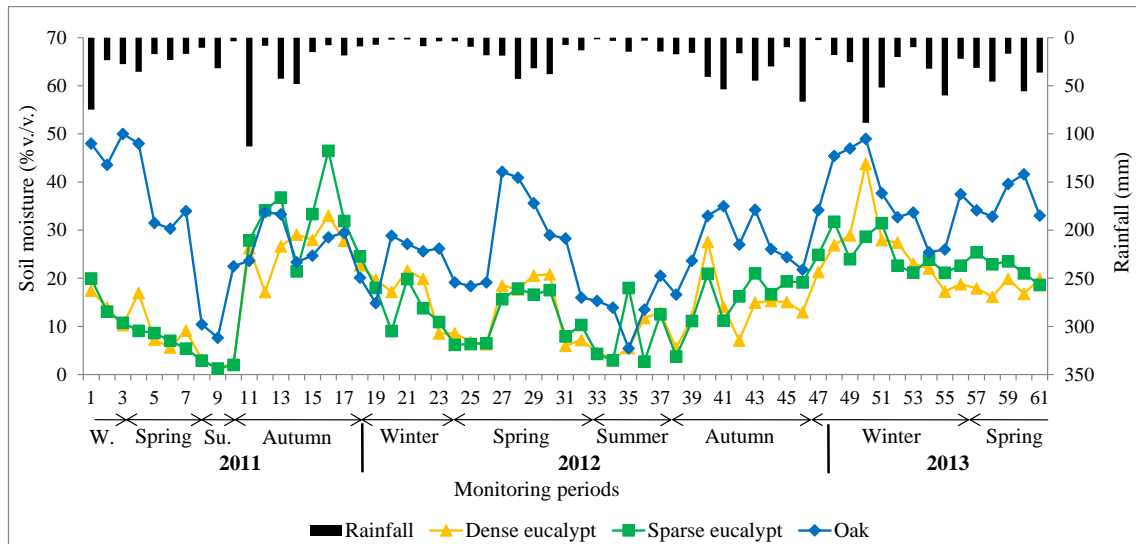


Figure 4 – Median surface soil moisture content per woodland type for the 61 measurement periods, from 9<sup>th</sup> February 2011 to 14<sup>th</sup> April 2013.

Figure 5

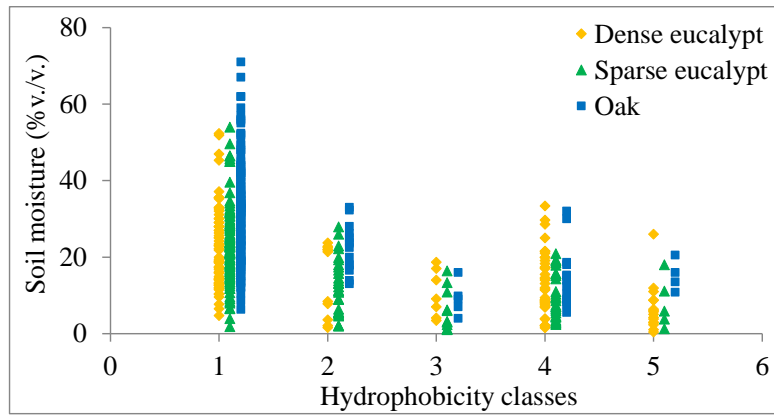


Figure 5 – Average soil moisture variability within hydrophobicity classes (1: wettable, 2: low, 3: moderate, 4: severe and 5: extreme hydrophobicity) for different forest types.

Figure 6

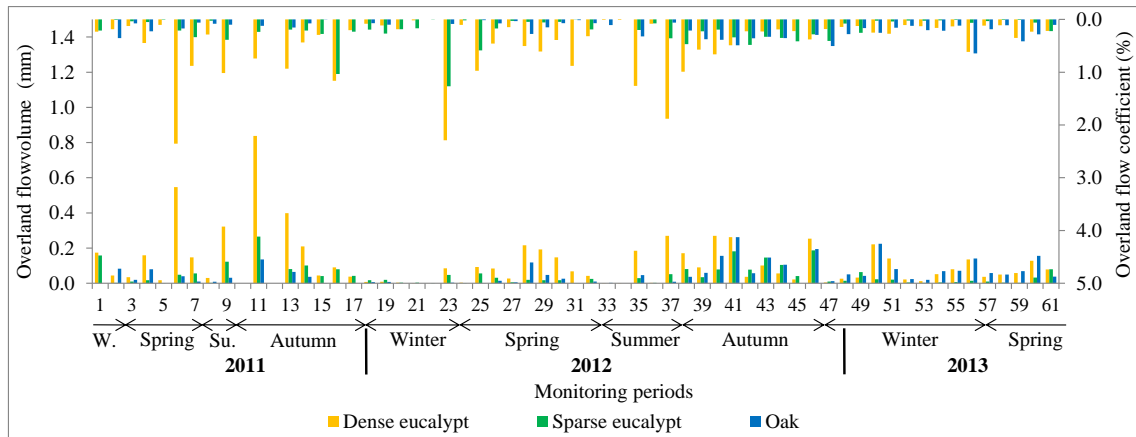


Figure 6 – Median overland flow, expressed as amount and percentage rainfall, per woodland type for the 61 measurement periods, from 9<sup>th</sup> February 2011 to 14<sup>th</sup> April 2013.

**Table 1**  
[Click here to download Table: Table\\_1.docx](#)

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

	Woodland type	Dense eucalypt			Sparse eucalypt			O1
	Plot reference	DE1	DE2	DE3	SE1	SE2	SE3	
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 <sup>-3</sup> )	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 no changes marked  
[Click here to download Table: Table\\_2.docx](#)

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

	Throughfall (mm)	Hydrophobicity			Soil moisture (%)	Overland flow
		0-2cm	2-5cm	5-10cm		
Rainfall (mm)	0.83**	-0.31**	-0.29**	-0.30**	0.25**	0
I <sub>30</sub> (mm h <sup>-1</sup> )	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**	0
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 <sup>-3</sup> )	-	-0.06	-0.05	-0.07	-0.21**	-0



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