



Swansea University
Prifysgol Abertawe



Cronfa - Swansea University Open Access Repository

This is an author produced version of a paper published in :
Journal of Hydrology

Cronfa URL for this paper:

<http://cronfa.swan.ac.uk/Record/cronfa21676>

Paper:

Ferreira, C., Walsh, R., Steenhuis, T., Shakesby, R., Nunes, J., Coelho, C. & Ferreira, A. (2015). Spatiotemporal variability of hydrologic soil properties and the implications for overland flow and land management in a peri-urban Mediterranean catchment. *Journal of Hydrology*, 525, 249-263.

<http://dx.doi.org/10.1016/j.jhydrol.2015.03.039>

This article is brought to you by Swansea University. Any person downloading material is agreeing to abide by the terms of the repository licence. Authors are personally responsible for adhering to publisher restrictions or conditions. When uploading content they are required to comply with their publisher agreement and the SHERPA RoMEO database to judge whether or not it is copyright safe to add this version of the paper to this repository.

<http://www.swansea.ac.uk/iss/researchsupport/cronfa-support/>

Manuscript Number: HYDROL17175R1

Title: Spatiotemporal variability of hydrologic soil properties and the implications for overland flow and land management in a peri-urban Mediterranean catchment

Article Type: Research Paper

Keywords: Soil moisture, soil hydrophobicity, infiltration capacity, Mediterranean, spatial and temporal variability, landscape units, overland flow, flow connectivity, urban hydrology

Corresponding Author: Mrs. Carla Sofia Santos Ferreira, MSc

Corresponding Author's Institution: CESAM - Centro de Estudos do Ambiente e do Mar

First Author: Carla Sofia Santos Ferreira, MSc

Order of Authors: Carla Sofia Santos Ferreira, MSc; Rory P Walsh, Prof.; Tammo S Steenhuis, Prof.; Richard A Shakesby, Prof.; João P Nunes, PhD; Celeste O Coelho, Prof.; António D Ferreira, Prof.

Abstract: Planning of semi-urban developments is often hindered by a lack of knowledge on how changes in land-use affect catchment hydrological response. The temporal and spatial patterns of overland flow source areas and their connectivity in the landscape, particularly in a seasonal climate, remain comparatively poorly understood. This study investigates seasonal variations in factors influencing runoff response to rainfall in a peri-urban catchment in Portugal characterized by a mosaic of landscape units and a humid Mediterranean climate. Variations in surface soil moisture, hydrophobicity and infiltration capacity were measured in six different landscape units (defined by land-use on either sandstone or limestone) in nine monitoring campaigns at key times over a one-year period. Spatiotemporal patterns in overland flow mechanisms were found. 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. In wet periods, saturation overland flow occurred on urban and agricultural soils located in valley bottoms and on shallow soils upslope. Topography, water table rise and soil depth determined the location and extent of saturated areas. Overland flow generated in upslope source areas potentially can infiltrate in other landscape units downslope where infiltration capacity exceeds rainfall intensity. Hydrophilic urban and agricultural-sandstone soils were characterized by increased infiltration capacity during dry periods, while forest soils provided potential sinks for overland flow when hydrophilic in the winter wet season. Identifying the spatial and temporal variability of overland flow sources and sinks is an important step in understanding and modelling flow connectivity and catchment hydrologic response. Such information is important for land managers in order to improve urban planning to minimize flood risk.

Carla Sofia Santos Ferreira
Rua da Tabueira nº8, Arnal
2405-004 Maceira, LRA
Portugal

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

I am enclosing herewith a manuscript entitled "Spatiotemporal variability of hydrologic soil properties and the implications for overland flow and land management in a peri-urban Mediterranean catchment" for evaluation and possible publication in Journal of Hydrology. The manuscript is a research paper prepared by Carla Ferreira, Rory Walsh, Tammo Steenhuis, Richard Shakesby, João Nunes, Celeste Coelho and António Ferreira. The submission includes four files: the main manuscript file which comprise 10021 words, a Figures file containing 10 figures (3 figures in colour), a Tables file containing 3 tables, and a Highlights file which presents the bullet points and main findings of the manuscript.

The manuscript presents field data as regards to the annual variability of soil moisture, hydrophobicity and soil matrix infiltration capacity in different landscape features of a periurban Mediterranean catchment. The results show the different behaviour of distinct landscape features as regards to the monitored hydrologic properties. The implications of the temporal and spatial variability of the soil properties on overland flow processes and flow connectivity are discussed, as well as the importance of its knowledge for hydrological modelling and urban planning, in order to mitigate flood hazards. We believe these findings and discussion will be of interest to the readers of your journal.

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

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

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

Carla Sofia Santos Ferreira

Carla Sofia Santos Ferreira (PhD student)
Centro de Estudos do Ambiente e do Mar
(Signature of corresponding author on behalf of all authors)

23rd May 2014

Highlights

- Variability of soil moisture, hydrophobicity and soil matrix infiltration capacity;
- Focus in a periurban Mediterranean catchment;
- Distinct landscape units show different temporal patterns;
- Understand how soil properties vary and its implications for flow connectivity;
- Implications for hydrological modelling and urban planning are discussed.

Replies to the Editors and Reviewers

Thank you for the comments. They helped to improve the manuscript greatly. The revised version of the manuscript addresses the points made by the reviewers. Most change has been made to the discussion, which Reviewer #2 felt needed some change and clarity. Major changes were made to Section 5.1 by re-organizing the information to present the landscape unit characteristics, rather than an explanation of the soil properties, as in the first version.

A few references were added to support some of the comments made views.

English improvements were also performed over the manuscript.

In the next section we respond to each of comments. We first indicate what the comment is and this is followed by our response.

SUMMARY OF COMMENTS OF DR KONSTANTINE P. GEORGAKAKOS, EDITOR

Please consider the reviews to see if revision would be feasible. Should you wish to resubmit you should explain how and where each point of the reviewers' comments has been incorporated. For this, use submission item "Revision Notes" when uploading your revision. Also, indicate the changes in an annotated version of the revised manuscript (submission item "Revision, changes marked"). Should you disagree with any part of the reviews, please explain why. To facilitate further review, add line numbers in the text of your manuscript.

RESPONSE:

In response to the editor, formatting corrections were made, particularly to the list of reference and to some of the figures. The fonts of the text of figures 1 and 2 were changed to accord with the rest of the manuscript. In the legend of figures 5 and 9, information was added in order to present all the graphs included within these figures. Formatting of affiliations with a lower-case superscript letter was also corrected.

COMMENTS OF THE ASSOCIATE EDITOR

The authors presented their research on the impact of variability in hydrologic soil properties on runoff and land management. The authors did a good job presenting their results. The discussion needs further work. The authors need to focus more on providing insights on the implications (as the paper title suggests). Such insights would be quite helpful to the readers.

RESPONSE:

In order to provide insights we revised section "5. Discussion" through a re-organization of the information with emphasis on the landscape units characteristics. This restructuring involved the division of the "Discussion" in two sections: "5.1 Characteristics of the landscape units and their influence on overland flow", which includes the information of section 5.1 and 5.2 of the previous version of the manuscript, and "5.2 Implications for catchment runoff delivery and land management", which is basically the previous 5.3 section. In the revised manuscript version, the new 5.1 section was sub-divided in four sections: "5.1.1 Woodland landscape units", "5.1.2. Urban landscape units", "5.1.3 Agricultural landscape units" and "5.1.4 Synthesis: the influences of lithology, topography and land-use factors on overland flow and temporal variation in its distribution within the Ribeira dos Covões catchment". The initial

three sub-sections focus on individual soil properties within each landscape unit, how they vary over the year and how they influence overland flow. Section 5.1.4 synthetize the relevant aspects of lithological, topographic and land-use factors influencing overland flow generation processes within the study catchment.

COMMENT:

The authors should address the detailed comments provided by the two reviewers and revise the manuscript accordingly.

RESPONSE:

The points made by the reviewers are addressed individually below.

COMMENTS OF REVIEWER #1

COMMENT:

The manuscript presented spatiotemporal variability of hydrologic soil properties in detail and the implications for overland flow based on the observations in the peri-urban Mediterranean catchment. Understanding how the spatial and temporal variability in overland flow generation in a catchment with varied land use/cover, geology and soils is very important for predicting flood hazards, development of the physically based rainfall runoff models, understanding the runoff processes, etc. This kind of data and discussions in the manuscript are very important topic in Hydrology, and spatial and temporal variation data of overland flow in the catchments should be published and shared with the other readers for better understanding of overland flow characteristics. So, I strongly recommend the manuscript be published in Journal of Hydrology. However, minor problems written in below should be revised before publication.

RESPONSE:

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

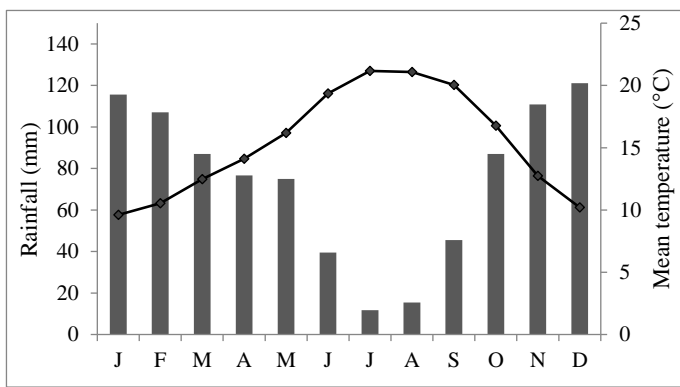
COMMENT:

Figure 1

Why did you focus on the two periods of 1941-1970 and 1971-2000 in Figure 1?? Please make a simple comment for this such as checking climate change or heat island effect. Otherwise, it may bring some confusions for the readers

RESPONSE:

Figure 1 has been changed to show the average values of the entire 1941-2000 period, instead of mean values of two periods:



“Figure 1 – Average monthly rainfall and temperature at Coimbra (Bencanta weather station), calculated from data regarding to the period 1941-2000 (INMG, 1941-2000).”

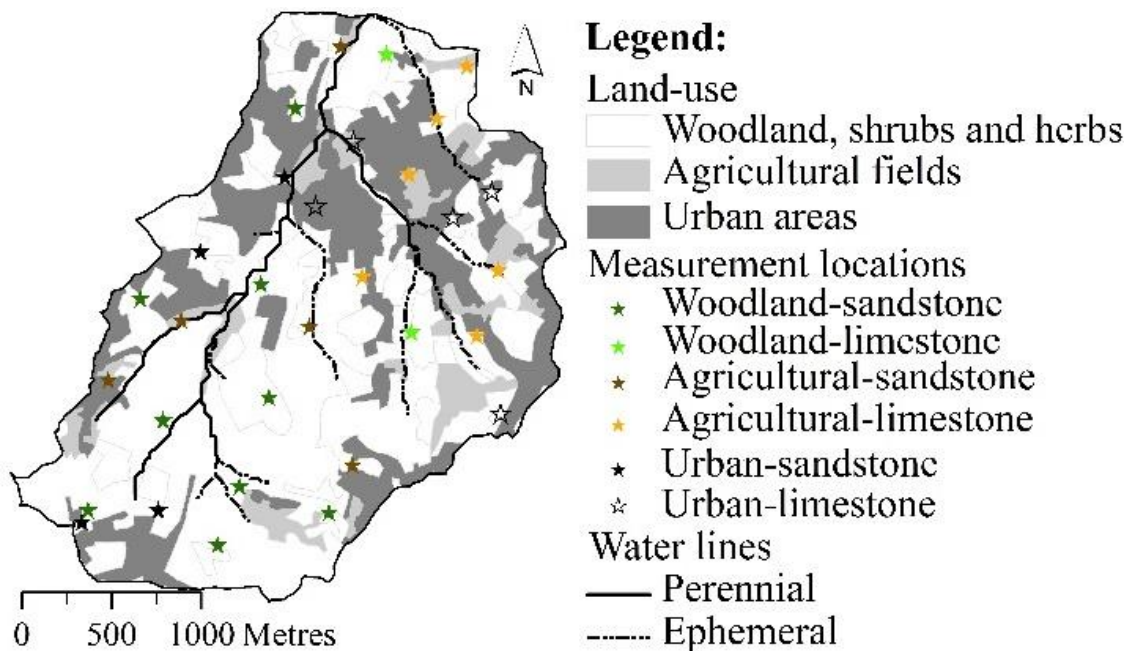
COMMENT:

Figure 2

Plots of measurement locations in Figure 2 are difficult to see the differences. Please make these plots bigger ones.

RESPONSE:

In Figure 2b, the symbols representing measurement sites have been enlarged.



COMMENT:

Figure 4

Where is the location of the observation station?? Please specify the location and distance from your target catchment. Otherwise, we cannot judge this data is appropriate for the reference of your target catchment

RESPONSE:

Information regarding temperature and rainfall source has been provided with an additional sentence added in the research design section (lines 144-146), as follows

“Temperature and rainfall data during the study period were provided by the national meteorological weather station 12G/02UG, located 0.5 km north of the study catchment.”

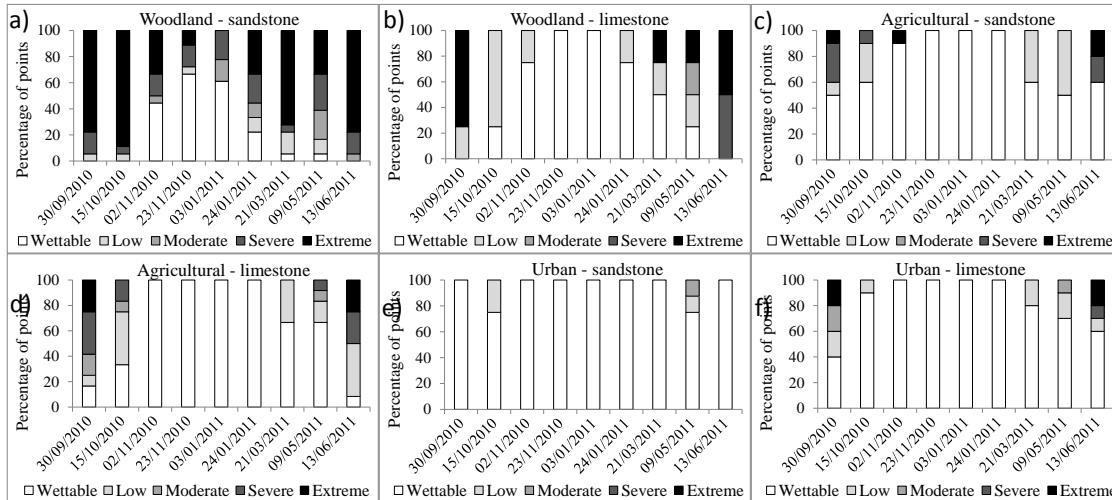
COMMENT:

Figure 5

Please write and specify (a), (b), (c),..., (f) in Figure 5.

RESPONSE:

In figure 5, sub-legends a), b)... have been inserted, as recommended:



“Figure 5 – Temporal variability of surface hydrophobicity for individual landscape units: a) woodland-sandstone, b) woodland-limestone, c) agricultural-sandstone, d) agricultural-limestone, e) urban-sandstone, f) urban-limestone.”

COMMENT:

pp.28, Line 616

If possible, please add a reference, data or something describe for 80, 50, and 10 years ago flood events.

RESPONSE:

The sentence presented on p.28, Line 650, has been re-written in order to clarify that the information about previous flood events was provided by local citizens during interviews, and so, no specific source can be added:

“According to interviews with older citizens, flooding events were already experienced about 80, 50 and 10 years ago, when the urban area was considerably less extensive than currently.”

COMMENTS OF REVIEWER #2

SUMMARY COMMENT

The authors measured hydrological properties in a peri-urban catchment. Sampling points were located in woodland, agricultural and urban settings, underlain by sandstone and limestone bedrock. The implications for hydrologic function and land management were

discussed.

Recommendation: Accept with moderate revisions

Major Comments

I found the Methods and results sections to be the best written and clearest that I have read in quite a while. What you did and how you was very well laid out and explained. The figures were similarly clear and helpful. I did not find the Discussion to be as clear, however. Throughout the Discussion, you explain possible explanations for your findings, but often without exploring what they mean. I agree that soil OM variability in woodlands could be due to management and tree type, but what are the implications for this? The entirety of Section 5.1 felt like a long list of the soil properties and explanations for every detail uncovered in the results section. By the time you discussed infiltration capacity of the woodland soils, I had forgotten what you said about the bulk density, and it was hard to see the big picture. Perhaps this is reflecting my bias as a catchment scale hydrologist, but I went into this paper excited to see how your analyses of these different landscape units would shed light on how land management affected larger scale hydrologic function (as laid out in your abstract). My suggestion would be to reorganize section 5.1 so that you move through the landscape units, describing how your findings explain their behavior. For instance, "Woodland environments have these properties, explained by this reason, resulting in this behavior. Sandstone substrate vs. Limestone results in this change in properties and behavior. If we move to an agricultural setting, these properties change due to this reason, resulting in this change in behavior. Etc..." This would include a lot of the same information that is included in Section 5.1 and 5.2, but organized in a way that allows the reader to see the bigger picture. I think this would also flow into section 5.3 on implications for land management.

RESPONSE:

Section 5.1 has been extensively changed in accordance with the reviewer's suggestion to clarify the different soil properties of each landscape unit, and explain how they interact in order to understand the temporal pattern of the infiltration capacity. The implications of soil properties in overland flow processes were also included in this section, based on an integration of previous sections 5.1 and 5.2 of the original manuscript version. The changes were as following:

"5.1 Characteristics of the landscape units and their influence on overland flow

5.1.1 Woodland landscape units

Woodland environments showed the highest soil organic matter content over the catchment. The high variability of this soil property within woodland areas may be due to differences in tree species and management practices affecting the litter layer thickness. The lower organic matter of eucalypt than other woodlands may reflect (a) periodic understorey clearance to help prevent wildfires and (b) low understorey vegetation caused by reduced water availability (DeBano, 2000). The generally low values of soil bulk density in woodland units may be the outcome of higher organic matter in woodland soils than in soils of the other landscape units and the denser root systems associated with a tree cover. Reduced bulk density is also characteristic of soils with greater organic matter, since it helps the formation of soil aggregates and structure (Celik et al., 2010).

The greatest soil hydrophobicity of woodland units can be linked to the species involved and their organic matter produced. Seasonal changes in hydrophobicity, with high values in summer and predominant disappearance in winter, was more pronounced in woodland than other landscape units and is in accordance with previous studies (e.g. Dekker and Ritsema,

1994; Doerr et al., 2000; Martínez-Zavala and Jordán-López, 2009). Within woodland, however, hydrophobicity was more extensive, severe and persistent in sites overlying sandstone than limestone (Figures 5a and 5b) Thus in woodland-sandstone areas a larger number of rainfall events was required for the soil to become hydrophilic, and even during the wettest periods, hydrophobicity persisted at a few sites. This is probably because sandstone areas are mainly dominated by eucalypt and pine plantations, whereas on limestone, oak is more dominant. The types of resins, waxes and aromatic oils produced by eucalypt (Doerr et al., 1998; Jordán et al., 2008) are thought to have caused hydrophobicity to be more extensive and resilient than in the other woodland stands, with hydrophobicity in eucalypt stands able to persist following rainfall of as much as 200 mm in 2 months (Ferreira, 1996; Doerr and Thomas, 2000). In contrast, in woodland-limestone areas, hydrophobicity was less severe and soil more easily switched to a hydrophilic state because oak, which is not usually associated with hydrophobic soil (Zavala et al., 2009), is the dominant vegetation.

Generally, woodland areas were also characterized by a more rapid re-establishment of hydrophobic conditions after rainfall events compared with the other landscape units, particularly in eucalypt plantations. The rate of re-establishment depends on the biological productivity of the ecosystem (Doerr and Thomas, 2000; Hardie et al., 2012), the type of hydrocarbon substances produced and microbial activity (Keizer et al., 2008). Santos et al. (in press) also report greater dynamism and more frequent hydrophobic conditions in eucalypt than in pine.

Nevertheless, differences in soil hydrophobicity between sandstone and limestone may also be linked to differences in particle size, given the statistically significant (albeit weak) positive correlation found between hydrophobicity and the sand fraction. This correlation has also been recorded elsewhere (e.g. DeBano, 1991; McKissock et al., 2000), although a few studies have reported hydrophobicity in relatively fine-textured soils (e.g. Doerr and Thomas, 2000). The higher evapotranspiration associated with a forest cover (e.g. Holden, 2008) may explain the low soil moisture contents recorded during dry periods in woodland, compared with the other land-uses (Figure 7), though shading by ground vegetation and litter can reduce soil moisture loss in warm, sunny conditions. The more intense hydrophobic conditions in eucalypt and pine woodland, by hindering infiltration (Dekker and Ritsema, 1994; Doerr and Thomas, 2000), might also help to explain the lower soil moisture results recorded in woodland-sandstone compared with limestone at times of transition from dry to wet conditions (15/10/2010 and 02/11/2011).

Despite the inverse correlation found between hydrophobicity and soil moisture content in the woodland units, no soil moisture threshold seems to determine the switching pattern between hydrophobic and hydrophilic soil properties. This accords with the inconsistent results recorded elsewhere. Thus in field experiments in Portugal, Leighton-Boyce et al. (2005) reported no threshold for up to 50% soil moisture content, whereas Doerr and Thomas (2000) found one at 28%. Reports of thresholds outside Portugal vary from 21% for medium-textured soils in SE Spain (Soto et al., 1994), to 38% for Dutch clayey peats (Dekker and Ritsema, 1994) and 50% for some organic-rich Swedish soils (Berglund and Persson, 1996).

The seasonal changes in soil hydrophobicity in woodland areas would explain the seasonal contrast in infiltration capacity. Thus, in summer when the woodland soil was at its driest and hydrophobicity was widespread, measured infiltration capacity was minimal, whereas in wettest weather in winter, the limited spatial extent of hydrophobicity allowed infiltration capacity to attain its highest values within *Ribeira dos Covões*. Nevertheless, the low inverse correlation coefficient found between infiltration capacity and hydrophobicity, despite being statistically significant, may have arisen because infiltration may sometimes have been delayed

by repellency, but on other occasions have commenced with switching to hydrophilic conditions by the end of the final 10 minutes of the 30 minutes measurement period.

Organic matter arguably plays a dual role in explaining the seasonal contrast in infiltration capacity in woodland units. Thus, although it is associated with hydrophobic conditions and low infiltration capacities in dry and transitional weather, in wet periods in winter, when hydrophobicity has largely disappeared, the same high levels of organic matter promote structured soils of high matrix infiltration capacity, representing the more typical situation of forest soils (e.g. Costa, 1999; Mouri et al., 2011).

The variations in hydrophobicity, soil moisture and infiltration capacity linked to geological and land-use controls and seasonal climatic influences discussed above result in spatiotemporal patterns of overland flow that differ seasonally and between woodland-sandstone and woodland-limestone areas. In storms following summer dry periods (e.g. following 30/09/2010 and 13/06/2010), drought-induced hydrophobicity in eucalypt and pine areas and the resulting very low matrix infiltration capacity make the woodland-sandstone areas particularly susceptible to infiltration-excess overland flow generation. In contrast, the less hydrophobic nature of the mainly oak vegetation of woodland-limestone areas means that they are less prone to infiltration-excess overland flow. Prolonged or repeated rainfall events led to partial switching of woodland soils to a hydrophilic state and reductions in spatial extent and severity of hydrophobicity. Hydrophobicity in eucalypt stands is more resistant to breakdown, requiring longer and/or a greater number of rainfall events. Because of this, infiltration capacity generally remained low in woodland sandstone areas (Figure 9a), and therefore prone to generate overland flow during transitions from dry to wet conditions, as recorded on 15th October 2010. In prolonged wet weather of the winter season, hydrophobicity largely disappeared even in woodland-sandstone areas, and no infiltration-excess overland flow occurred. Even under the wettest winter conditions, woodland areas showed relatively low soil moisture and high infiltration capacities and saturation overland flow was rare.

The potential for infiltration-excess overland flow in woodland landscape units in dry summer conditions was confirmed by rainfall simulation experiments, when a 43 mm h⁻¹ simulated rainfall produced runoff coefficients of 20-83% in a small plot (0.25 m²) in extremely hydrophobic woodland soil (slope: 5-36°) (Ferreira et al., 2012b).

On larger runoff plots (16m²) in woodland, however, under extremely hydrophobic conditions, overland flow did not exceed 3% even for a 23mm natural rainfall event (Ferreira et al., 2012a), mainly because of infiltration bypassing the hydrophobic soil matrix via macropores that can be provided by root-holes, invertebrate activity and high concentrations of stones (e.g. Urbanek and Shakesby, 2009; Hardie et al., 2011). Such bypass (preferential) flow is viewed as an important mechanism not only in extremely hydrophobic soils (Doerr and Thomas, 2000), but also in dry loamy soils with high clay and silt contents (Yang and Zhang, 2011; Bracken and Croke, 2007). Certainly, cracks in clay soils were observed in dry conditions during fieldwork in the catchment study.

5.1.2 Urban landscape units

In contrast to woodland, areas of urban landscape units in the *Ribeira dos Covões* catchment are characterized by the lowest soil organic matter content. This is probably linked to the reduced and patchy vegetation cover and, in some locations, either loss or re-deposition of surface soil. The higher bulk density may be largely due to compaction by people and vehicles (Silva et al., 1997), as a result of vehicle access and parking in the discontinuous urban fabric. Soil bulk densities measured (1.07-1.72 g cm⁻³) were similar to those (1.19-1.62 g cm⁻³)

reported in Nanjing, China, where lowest values were recorded in greenbelt areas and highest in parking zones (Yang and Zhang, 2011).

In the *Ribeira dos Covões* catchment, the dominance of bare surfaces and sparse grass and shrub vegetation is the main cause of the recorded widespread hydrophilic conditions throughout the year. Only at particularly well vegetated sites was hydrophobicity recorded during the driest periods. Bare soil sites, mainly found on sandstone, being more susceptible to evaporation (Nunes et al., 2011), may have led to the low soil moisture content recorded particular in dry-wet transitional periods, such as in the southwest of the catchment on 02/11/2010 and 21/03/2011 (Figure 8).

The generally hydrophilic conditions found in urban soil would help to explain the high soil matrix infiltration capacity values recorded particularly after prolonged dry weather (Figure 9), despite the high bulk density, which elsewhere has been noted to be associated with lower infiltration capacities (e.g. Dornauf and Burghardt, 2000; Yang and Zhang, 2011). The very low and in some cases zero values of soil matrix infiltration capacity recorded during wet periods may be linked to a decline in the suction force and then saturation of the soil. The inverse correlation recorded between soil moisture and infiltration capacity was also found in Tasmania by Hardie et al. (2012), where the application of dye tracer showed infiltration to an average depth of 1.03 m (with a wetting front velocity of 1160 mm h⁻¹) in low antecedent soil moisture conditions, compared with a depth of 0.35 m (and a wetting front velocity of 120 mm h⁻¹) with wet antecedent conditions.

In urban landscape units, overland flow is readily generated on impervious paved and tarmac surfaces, but for urban soils it varies in importance both seasonally and between urban-sandstone and urban-limestone areas. In dry summer conditions, the generally hydrophilic soils of greater infiltration capacity (Figures 9 and 10) lead to little or no overland flow and make these areas overland flow sinks. In contrast, after larger winter storm events, soil saturation or near-saturation was identified at urban-limestone sites (Figures 7 and 8) associated with a near-surface water table (on the valley floor) and shallow soils of low water storage capacity (on hillslopes). In both situations, saturation overland flow was at least being generated locally. In contrast, in urban soils on sandstone, moisture levels recorded in winter were much lower than on limestone (Figure 7) and infiltration capacities (Figure 9) varied from low (on bare soil) to relatively high (on uncompacted, vegetated sites); the result was patchy Hortonian overland flow, mostly on the bare soil areas, with some of the vegetated patches acting as overland flow sinks.

The potential for overland flow generation in urban soils was demonstrated by runoff coefficients of 59-99% recorded on hydrophilic urban soils (slope: 6-30°) in 43 mm h⁻¹ rainfall simulations on small plots (0.25 m²) at the field sites, though it was unclear whether the overland flow was infiltration-excess or saturation in nature (Ferreira et al., 2012b).

5.1.3 Agricultural landscape units

In agricultural landscape units, different land-use/land management types led to major differences on surface cover and soil properties. The agricultural types on sandstone (mainly pasture, small gardens and olive plantations) may explain the low organic matter content and high bulk density results of that landscape unit compared with the agricultural-limestone unit, where abandoned fields undergoing natural vegetation succession are dominant. This greater vegetation cover with higher soil organic matter content for agricultural-limestone would also explain the unit's enhanced spatial extent and severity of hydrophobicity than on sandstone. Nevertheless, hydrophobicity at agricultural-limestone sites was less severe than in woodland, and fewer rainfall events were required to accomplish switching from hydrophobic to

hydrophilic conditions, and hydrophobicity re-establishment in wet to dry transitions was also slower than for woodland (Figure 5). In a previous study of a partly urbanized Mediterranean catchment, Fernández and Ceballos (2003) only recorded lower hydrophobicity persistence when conditions were changing from dry to wet.

The generally higher soil moisture values of agricultural compared with other landscape units, despite the absence of irrigation, may be explained by the lower vegetation cover of the agricultural-limestone sites together with their low hydrophobicity, particularly when compared with woodland. In addition, high surface roughness associated with tillage in agricultural-sandstone fields may enhance surface water retention and lead to higher soil moisture (Álvares-Mozos et al., 2009), especially when compared with untilled urban soils.

Soil moisture, however, was slightly higher at agricultural-limestone than agricultural-sandstone sites, despite most of the former being abandoned. This may be a consequence of the marly nature of the limestone, resulting in a higher proportion of fine material. However, the small soil moisture difference may reflect the fact that most sandstone agricultural sites are on valley floors (Figure 8), and thus often generally moist, whereas limestone sites are mainly on upper slopes, where the soil is shallow (generally <40 cm depth) and often dry, though in the wettest periods some saturation was observed here.

Differences in particle size distribution and land management practices, particularly wheeling, may explain higher soil porosity on abandoned limestone than on ploughed sandstone fields. Nevertheless, a coarser particle size distribution and relatively weak hydrophobicity may explain greater soil matrix infiltration capacity on sandstone compared with limestone agricultural areas in dry periods.

Increasing soil moisture content during the wet season, however, could reduce soil matrix infiltration capacity in agricultural areas, which was mostly apparent on sandstone fields. In agricultural-limestone sites, matrix infiltration capacity was relatively constant during the year. In this landscape unit, the slight infiltration capacity increase during early autumn, possibly due to soil hydrophobicity reduction, gives way to a decreasing capacity in later autumn and winter seasons, as a result of soil moisture increase. Throughout spring, with soil moisture decreasing, infiltration capacity first tends to increase but later, possibly as a result of hydrophobicity re-emergence at some sites, then reduces once more. The development of hydrophobic conditions in the agricultural soils, however, was clearly slower than in woodland (Figure 5).

In response to the contrasts in soil moisture, hydrophobicity and infiltration capacity and their seasonal dynamics discussed above, overland flow generation varied between agricultural-sandstone and agricultural-limestone landscape units. In the former, high infiltration capacities associated with continuously hydrophilic sandy soils meant that overland flow was absent in summer and in winter was only generated in big events or following very wet weather. In contrast, the greater vegetation of the abandoned fields on limestone led to hydrophobic soils in summer and a degree of proneness to infiltration-excess overland flow. Despite partial switching in transition periods and total switching to hydrophilic conditions in winter wet periods, the relatively low infiltration capacities and high soil moisture resulting from the marly limestone lithology meant that the agricultural limestone areas were more prone in winter to saturation overland flow than the sandstone areas.

Unlike on urban and woodland soil sites, no infiltration-excess overland flow was recorded in 43 mm h⁻¹ rainfall simulation experiments on hydrophilic agricultural-sandstone land (slope gradients, 15-40°) in the study area (Ferreira et al., 2012b).

5.1.4 Synthesis: the influences of lithology, topography and land-use factors on overland flow and temporal variation in its distribution within the *Ribeira dos Covões* catchment

Lithology seems to play an important role in controlling spatiotemporal dynamics of overland flow in the *Ribeira dos Covões* catchment via its influence on particle size distribution, soil moisture and infiltration capacity variability over the catchment. Generally, the greater sand fractions and deeper soils of the sandstone areas promote greater infiltration capacity and water storage capacity, and lower soil moisture, leading to reduced proneness to both Hortonian and saturation overland flow. In contrast, the higher silt-clay content and shallower nature of soils on the marly limestone result in greater soil moisture, lower infiltration and water storage capacities and hence greater proneness to saturation overland flow than on sandstone. These effects are in line with reports elsewhere of the influence on overland flow of shallow soils (Easton et al., 2007, Hardie et al., 2011) and variations in particle size (Rahardjo et al., 2008; Yang and Zhang, 2011).

Local topographic characteristics represent a second important influence on overland flow dynamics. Saturation was observed at urban soil sites near streams (Figure 8) caused either by (1) lateral subsurface flows from upslope (Aryal et al., 2005) or (2) groundwater table rise, as recorded at a woodland-sandstone site near to an active spring on 24th January 2011 (Figure 8). In a small cultivated Mediterranean catchment in the Pyrenees, Latron and Gallart (2007) also related the saturation pattern to the extent and height of the water table. The locations and extents of the wettest areas in the *Ribeira dos Covões* catchment varied temporally, a feature also reported elsewhere within agricultural hillslope (Walter et al., 2000) and mixed agricultural and forested (Easton et al., 2007) areas.

Land-use and land management constitute the third and perhaps most important influence on differences in overland flow between and within landscape units. This influence is exerted through the effects of different percentage ground covers, management practices and other human activities on degrees of soil compaction, soil moisture levels and soil permeability and via the effects of different plant species on hydrophobicity severity, switching dynamics and seasonality. Overland flow is consequently of greatest significance in urban landscape units, particularly in winter, when urban soils are often either saturated or bare and compacted, whereas in summer overland flow from impervious or bare areas is reduced by hydrophilic soil patches. Overland flow in the woodland units is in general greatly reduced by vegetation effects on infiltration, but is seasonally enhanced in storms following summer dry periods in eucalypt and pine woodland-sandstone areas because of their severe soil hydrophobicity, but absent in woodland-limestone areas because of the oak woodland land-use. The agricultural-sandstone landscape unit produces very little overland flow because of high infiltration capacities resulting from a combination of land-use and land management practices that do not result in compaction, but mostly because of the sandy soils. In converse fashion, the abandoned field land-use of agricultural-limestone areas probably has the effect of reducing overland flow responses from what they would otherwise be with active cultivation, although for lithology-related reasons responses can still be significant particularly in winter wet weather.

Differences in temporal variability of soil hydrological properties between landscape units led to spatial fluctuation in overland flow sources and sinks. In wet winter conditions, overland flow is greatest from the urban landscape units and also significant from the agricultural-limestone unit, but comparatively little is generated on the hydrophilic and permeable agricultural-sandstone and woodland units except in the wettest weather. During transitions from wettest to dry conditions, the spatial pattern of response to rainstorms is reversed, with decreasing susceptibility to saturation overland flow as soil moisture declines (particularly in agricultural- and urban-limestone areas) and increasing vulnerability to infiltration-excess overland flow, enhanced by hydrophobicity re-establishment (particularly in woodland but also

agricultural-limestone units). In summer, overland flow is comparatively low but still greatest in urban-limestone areas and to a lesser extent is also significant in the woodland and agricultural-limestone units because of their hydrophobic condition, but urban-sandstone and agricultural-sandstone areas produce comparatively little overland flow, because of at least locally hydrophilic and permeable surface soils providing overland flow sinks. Finally, in the dry to wet transition of autumn, patterns of overland flow are broadly similar to the wet-to-dry transition, with hydrophobicity (and overland flow responses) becoming most rapidly re-established in eucalypt areas of the woodland-sandstone landscape unit.

Spatial variability of soil properties *within* the same landscape unit, such as particle size and hydrophobicity, provides heterogeneous infiltration capacities, where this particularly applies to (a) the partly bare urban-sandstone unit and (b) the woodland and agricultural-limestone units in transitional periods (Figure 9). Soil spots with matrix infiltration capacity lower than rainfall intensity will lead to local infiltration-excess overland flow, which may be infiltrated in surrounding soil spots of greater infiltration capacity. Not all landscape units provided spots with sufficient permeability throughout the year. Urban and agricultural landscape units showed more sites of high permeability after dry periods, while even in the wettest conditions, woodland provided sites of high infiltration capacity. Nevertheless, even the most permeable soil patches could not cope with the maximum rainfall intensity of 15.6 mm h⁻¹ recorded in the rainstorm of 2nd November 2011. Thus infiltration-excess overland flow would be expected to occur widely during particularly intense storms in all landscape units.”

MINOR COMMENTS

Re-writing of section 5.1 involved moving some text to locations in other parts of the manuscript. In order to clarify the changes made, the new lines are presented.

COMMENT:

Line 58. I would spell out which factors you are talking about, as this is the first sentence in a paragraph

RESPONSE:

The sentence was repositioned in the previous paragraph in order to avoid repetition of the long list of factors, as in the original version:

“...Variations in surface soil moisture, hydrophobicity and infiltration capacity were measured in six different landscape units (defined by land-use on either sandstone or limestone) during nine monitoring campaigns at key times over a one-year period.

Spatiotemporal patterns in overland flow mechanisms were found. 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.”

COMMENT:

Line 68. Mediterranean climates or locations?

RESPONSE:

The word “climate” has been added to the sentence in order to clarify the idea.

“**Although** there have been many studies of soil hydrophobicity and its impacts on infiltration and overland flow in a range of seasonal and sub-humid environments (e.g. Glenn and Finley, 2010; Carrick et al., 2011; Orfánus et al., 2014), **in areas of Mediterranean climate** they have been mainly **focussed on forested terrain...**”

COMMENT:

Line 71. I would replace "Relatively little, furthermore, is..." with "Furthermore, relatively little is..."

RESPONSE:

The beginning of the sentence has been re-written:

"Furthermore, relatively little is known about..."

COMMENT:

Line 80. The term peri-urban is not in common usage everywhere (i.e. USA) - I would give a short definition.

RESPONSE:

Additional information has been added to clarify the term peri-urban:

"This is even truer of peri-urban areas, which represent the transition zone between urban and rural environments."

COMMENT:

Line 102. I would remove "only"

RESPONSE:

Word "only" has been removed:

"...hot and dry summers (8% of rainfall in the months June-August)..."

COMMENT:

Line 134. Mainly or entirely?

RESPONSE:

Word "mainly" has been deleted twice, since the descriptions applied to all the sites:

"... 4 on sandstone (bare soil sites associated with construction and open spaces with ground vegetation between houses) and 5 on limestone (derelict spaces between houses and houses and roads)."

COMMENT:

Line 236. I would replace "Overall rainfall and temperature during..." with "Rainfall and temperature patterns during..."

RESPONSE:

The suggested improvement has been made:

"Rainfall and temperature patterns during the monitoring period..."

COMMENT:

Line 244. The % symbol seems unnecessary - frequency implies the %...

RESPONSE:

% symbol removed:

"Soil hydrophobicity varied greatly in severity and frequency both..."

COMMENT:

Line 280. 2010 instead of 3010

RESPONSE:

The year was corrected:

"...periods (30/09/2010 and 13/06/2011), soil..."

COMMENT:

Line 284. It is unclear what the vice versa refers to - the two land uses, or the wet/dry transitions.

RESPONSE:

The sentence has been re-written in order to clarify that *vice versa* was referring to the wet/dry transition:

“Soil moisture was generally lower in urban sandstone soils throughout the year, but also on woodland sandstone in winter and in dry-wet and wet-dry transition periods.”

COMMENT:

Line 320. I would replace "variable" with "high variability"

RESPONSE:

“high variability” has been adopted. It is now presented on line 331:

“The high variability of this soil property...”

COMMENT:

Line 322-323. Be consistent with spelling of understory (understorey). My understanding is both spellings are correct.

RESPONSE:

The spelling has been unified as recommended. It is now presented on line 332-335.

“The lower organic matter of eucalypt than other woodlands may reflect (a) periodic understorey clearance to help prevent wildfires and (b) low understorey vegetation caused by reduced water availability (DeBano, 2000).”

COMMENT:

Line 359. Mostly or only?

RESPONSE:

The sentence has been fully re-written. It is now presented on line 442-445:

“In the Ribeira dos Covões catchment, the dominance of bare surfaces and sparse grass and shrub vegetation is the main cause of the recorded widespread hydrophilic conditions throughout the year. Only at particularly well vegetated sites was hydrophobicity recorded during the driest periods.”

COMMENT:

Line 362 & 364. The phrase "break down" feels awkward. Perhaps simply remove in first sentence, and replace "easier to break down" with resistant in the second.

RESPONSE:

Re-writing of the section has led to significant changes to the sentence. However, the term “breakdown” has been avoided in all the manuscript. For example:

“...hydrophobicity was less severe and soil more easily switched to a hydrophilic state ...”
(line 355)

“...when hydrophobicity has largely disappeared...” (line 398)

COMMENT:

Line 378. Replace "...correlation, although weak..." with "...weak correlation..." if true

RESPONSE:

The word “weak” has been deleted, since despite being weak, the correlation is statistically significant, and other studies have reported stronger significant correlations. The sentence was re-written as below, as can be seen on line 367-368 of the revised version:

“Nevertheless, differences in soil hydrophobicity between sandstone and limestone may also be linked to differences in particle size, given the statistically significant (albeit weak) positive correlation found between hydrophobicity and the sand fraction. This correlation has also been recorded elsewhere (e.g. DeBano, 1991; McKissock et al., 2000), although a few studies have reported hydrophobicity in relatively fine-textured soils (e.g. Doerr and Thomas, 2000).”

COMMENT:

Line 380. Missing a "can."

RESPONSE:

The sentence was removed in the new version of the manuscript.

COMMENT:

Lines 384-390. I am not sure what the point of this review was - did you see a different threshold? How does this threshold impact your findings?

RESPONSE:

The sentence has been re-written in order to clarify that our findings do not show a soil moisture threshold for changing hydrophobic properties, and that other studies have also considered this issue. The relevant text can now be found on line 378-381 in the revised version:

“Despite the inverse correlation found between hydrophobicity and soil moisture content in the woodland units, no soil moisture threshold seems to determine the switching pattern between hydrophobic and hydrophilic soil properties. This accords with the inconsistent results recorded elsewhere. ...”

COMMENT:

Line 398. Remove "mainly"

RESPONSE:

The sentence has been re-written. It can be found on line 442-444 of the new version of the manuscript:

“...the dominance of bare surfaces and sparse grass and shrub vegetation is the main cause of the recorded widespread hydrophilic conditions throughout the year...”

COMMENT:

Line 400. "such as in the urban landscape units"

RESPONSE:

The sentence has been re-written. It can be seen on line 445 of the new version of the manuscript:

“Bare soil sites, mainly found on sandstone, being more susceptible to evaporation ...”

COMMENT:

Line 406. "Woodlands are..."

RESPONSE:

All the sentence has been re-written. Please see line 395-400.

“Thus, although it is associated with hydrophobic conditions and low infiltration capacities in dry and transitional weather, in wet periods in winter, when hydrophobicity has largely disappeared, the same high levels of organic matter promote structured soils of high matrix infiltration capacity, representing the more typical situation of forest soils (e.g. Costa, 1999; Mouri et al., 2011).”

COMMENT:

Line 432. Higher clay and silt content, rather than nature, correct?

RESPONSE:

Sentence re-written to clarify the idea. Please see now line 499:

“This may be a consequence of the marly nature of the limestone, resulting in a higher proportion of fine material.”

COMMENT:

Line 433. I would expect lower clay content soils to have higher infiltration capacity simply due to soil texture as well (sand > clay).

RESPONSE:

The sentence has been re-written as follows (lines 541-546):

“. In contrast, the higher silt-clay content and shallower nature of soils on the marly limestone result in greater soil moisture, lower infiltration and water storage capacities and hence greater proneness to saturation overland flow than on sandstone, These effects are in line with reports elsewhere of the influence on overland flow of shallow soils (Easton et al., 2007, Hardie et al., 2011) and variations in particle size (Rahardjo et al., 2008; Yang and Zhang, 2011).”

COMMENT:

Line 457-461. The purpose of this paragraph is unclear - to explain the correlation, or to explain the weakness of the correlation.

RESPONSE:

The idea was clarified by re-writing of the first part of the sentence (See line 455-456 in the new version):

“The inverse correlation recorded between soil moisture and infiltration capacity for urban soils was also found in Tasmania...”

COMMENT:

Line 464. I would qualify the statement about hydrophobicity, as this is an inference. "...organic matter content, most likely due to increased hydrophobicity."

RESPONSE:

The sentence relating the organic matter content with hydrophobicity was re-written in the new version of the manuscript (lines 340-341):

“The greatest soil hydrophobicity of woodland units can be linked to the species involved and their organic matter produced.”

COMMENT:

Line 432. I would move the citation earlier in this paragraph (end of first sentence) to make it clear that this is a citation and not new results.

RESPONSE:

The sentence has been re-written to make it clear that it was a citation and not a result (lines 552-555):

“The locations and extents of the wettest areas in the Ribeira dos Covões catchment varied temporally, a feature also reported elsewhere within agricultural hillslope (Walter et al., 2000) and mixed agricultural and forested (Easton et al., 2007) areas.”

COMMENT:

Line 452-456. This needs a citation

RESPONSE:

The sentence has been re-written, but a reference to “Costa, 1999” has been included (line 398-400):

“when hydrophobicity has largely disappeared, the same high levels of organic matter promote structured soils of high matrix infiltration capacity, representing the more typical situation of forest soils (e.g. Costa, 1999; Mouri et al., 2011).”

and added to the reference section:

“Costa, J.B., 1999. Caracterização e constituição do solo, 6ª edição. Fundação Calouste Gulbenkian, Lisboa.”

COMMENT:

Line 457. "...correlation between hydrophobicity..."

RESPONSE:

The role canopy storage and aerodynamic conductance on water losses has been clarified and rewritten (lines 619-620):

“...Valente et al. (1997) reported relatively high interception losses of 17% in *Pinus pinaster* forest and 11% in eucalypt stands and attributed them to the greater canopy storage and, aerodynamic roughness (and hence higher evaporation rates) of forest covers.”

COMMENT:

Line 558. Compared not comparing

RESPONSE:

The suggestion to replace “comparing” by “compared” was implemented (line 621):

“...greater litter density and frequency of root holes compared with...”

COMMENT:

Line 560. Despite or because of?

RESPONSE:

The sentence was re-written (see on line 630):

“Vegetation is widely considered as a key factor interrupting hydrological connectivity ...”

COMMENT:

Line 562. Positive is a biased word - I would remove.

RESPONSE:

The sentence has been removed in the new manuscript version.

COMMENT:

Line 575. I think you could find many references here, not limited to Pennsylvania. The work of Tromp-van Meerveld, Uchida, Woods, Graham etc... come to mind.

RESPONSE:

Two additional references have been included (line 636-638):

“preferential flow via macropores can reach streams relatively quickly, and thus contribute to the flood peak, as reported in other areas of the world (Uchida et al., 1999; van Schaik et al., 2008; Yu et al., 2014)”

and included in the list of References section:

“Uchida, T., Kosugi, K., Miizuyama, T., 1999. Runoff characteristics of pipeflow and effects of pipeflow on rainfall-runoff phenomena in a mountainous watershed. J. Hydrol. 222(1-4), 18-36.”

“van Schaik, N.L.M.B., Schnabel, S., Jetten, V.G., 2008. The influence of preferential flow on hillslope hydrology in a semi-arid watershed (in the Spanish Dehesas). Hydrol. Process. 22(18), 3844-3855.”

COMMENT:

Line 604. "together"

RESPONSE:

“together” has been replaced by “such as”. It is now presented on line 666-668:

“Even if urban soils surrounding impermeable surfaces (e.g. roofs and roads) cannot act as sinks, obstructions (such as buildings and walls) may delay overland flow transfer.”

COMMENT:

Line 672. "...vegetation, litter and surface..."

RESPONSE:

"...vegetation, litter and surface..." change was implemented (now on line 736):

“Despite the generally low soil matrix infiltration capacity across the catchment, macropores, vegetation, litter and surface roughness...”

COMMENT:

Figure 1. Why is the precip split between pre and post 1970? I don't recall discussion in the text...

RESPONSE:

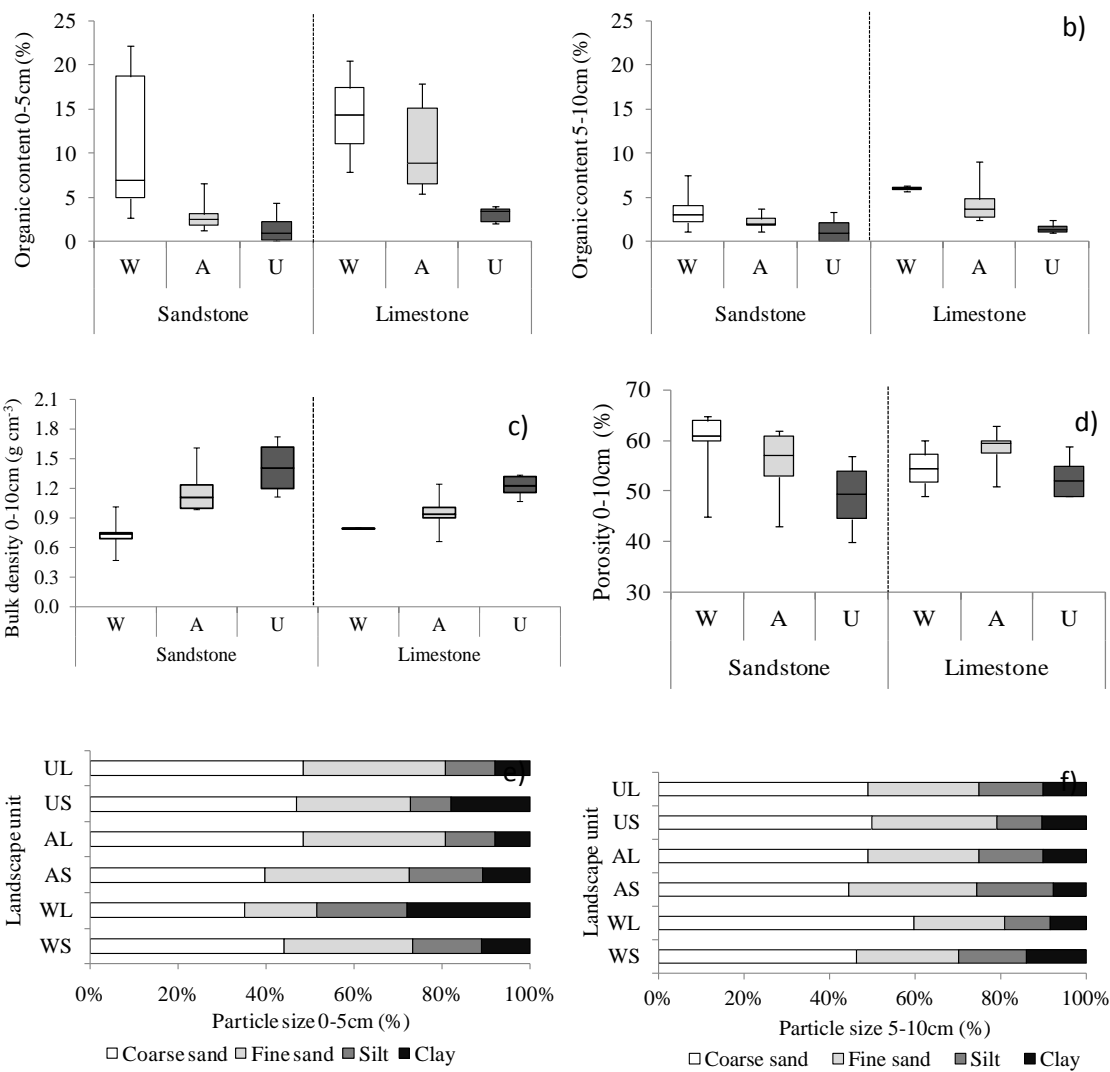
Figure 1: The figure has been changed to show the average values of the entire 1941-2000 period, as explained also to reviewer #1.

COMMENT:

Figure 3. The capitalization is not consistent (Coarse sand v Coarse Sand; Bulk Density v Landscape unit)

RESPONSE:

Use of upper case letters has been standardized:

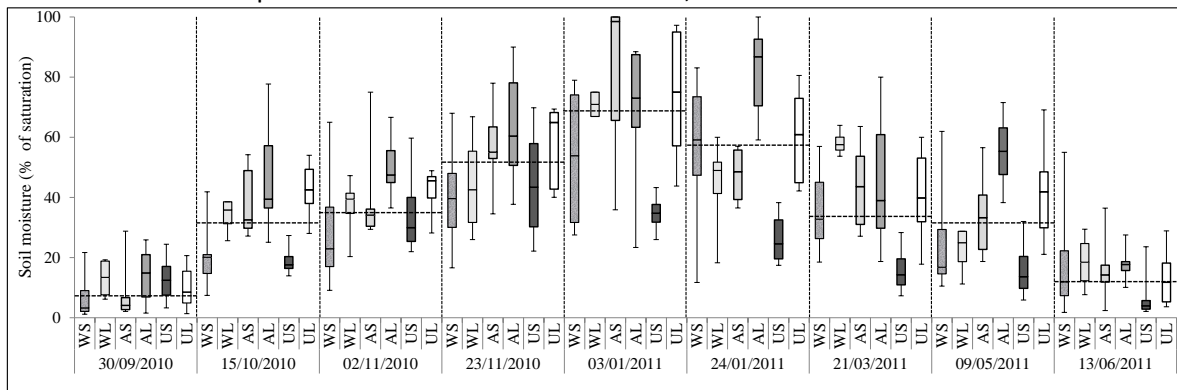


COMMENT:

Figure 3/7. I would be consistent with either WS notation or W/S between figures

RESPONSE:

Reference to landscape units has now been standardized, as recommended:



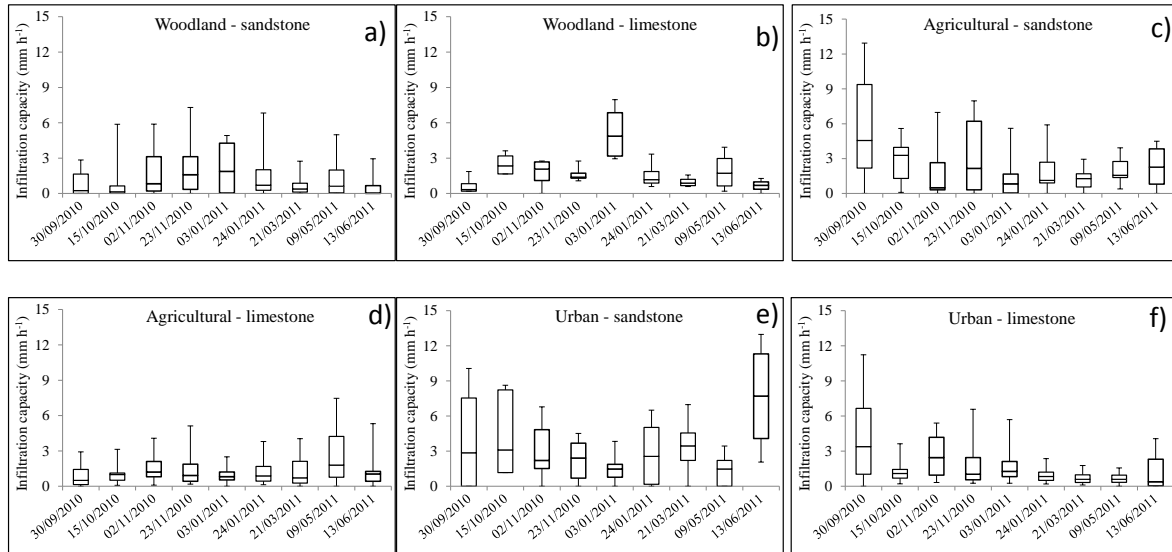
COMMENT:

Figure 8. Remove or adjust dashed line - it does not really show the pattern. On the WL site, for instance, the dashed line diverges greatly from the measured ranges on 21/11/2010,

24/1/2011, etc... I would allow the reader to see the pattern themselves, or put a dashed line that connects median values.

RESPONSE:

We believe that the comment was referring to Figure 9 instead of Figure 8. The idea of the dashed lines had been to indicate the overall pattern between dry and wet seasons, but it was not properly explained in the legend. However, agreeing with the reviewer comment, since there are quite differences between the measured values and the dashed lines, we have followed the suggestion to remove them from the figure, and allow the reader to observe the pattern. Additional letters to refer each component figure have been inserted and are included within the legend:



“Figure 9 – Box plots of temporal variability of matrix soil infiltration capacity for each landscape unit: a) woodland-sandstone, b) woodland-limestone, c) agricultural-sandstone, d) agricultural-limestone, e) urban-sandstone, f) urban-limestone”.

COMMENT:

Figures 6, 8 and 10. I would say that the data is distributed using the Thiessen Polygon method.

RESPONSE:

Reference to the Thiessen Polygon method has been added to the legend of figure 10. As regards figures 6 and 8, the reference to the method was already presented in the legends.

“Figure 6 – Spatial variation of median soil hydrophobicity at the measurement dates, based on the Thiessen polygon method.”

“Figure 8 – Spatial distribution in median soil moisture content for each the measurement date, using the Thiessen polygon method.”

“Figure 10 - Spatial variation in median matrix soil infiltration capacity at each measurement date, using the Thiessen Polygon method.”

COMMENT:

Table 1. Add .0 for whole numbers in total rainfall column (66.0, 97.0, 37.0), unless instrument precision changed for that period.

RESPONSE:

The decimal numbers have been adjusted as suggested:

Measurement date	Total rainfall between measurements (mm)	Antecedent rainfall (mm)				Mean temperature during previous 5 days (°C)
		2 days	5 days	10 days	30 days	
30/09/2010	-	0.0	0.0	0.0	5.0	18.9
15/10/2010	72.6	0.0	0.2	53.8	72.6	16.7
02/11/2010	77.2	1.2	75.4	77.2	131.6	14.1
23/11/2010	66.0	0.4	9.6	49.0	141.8	11.4
03/01/2011	161.5	0.5	26	30.2	131.5	12.3
24/01/2011	82.8	0.7	2.6	12.3	112.5	6.9
21/03/2011	97.0	0.2	0.2	15.8	19.8	13.1
09/05/2011	72.3	0.2	3.1	12.5	47.2	16.3
13/06/2011	37.0	0.0	0.0	0.0	37.0	18.1

1

2 **Spatiotemporal variability of hydrologic soil properties and the implications for**
3 **overland flow and land management in a peri-urban Mediterranean catchment**

4

5 C. S. S. Ferreira^{a,b}, R. P. D. Walsh^c, T. S. Steenhuis^d, R. A. Shakesby^c, J. P. N. Nunes^a, C.
6 O. A. Coelho^a, A. J. D. Ferreira^b

7

8 ^a *CESAM, Department of Environment and Planning, University of Aveiro, Aveiro,*
9 *Portugal*

10 ^b *CERNAS, Coimbra Agrarian Technical School, Bencanta, Coimbra, Portugal*

11 ^c *Department of Geography, College of Science, Swansea University, Swansea, United*
12 *Kingdom*

13 ^d *Department of Biological and Environmental Engineering, Cornell University, Ithaca,*
14 *New York, USA*

15

16 **Corresponding author:** Carla Ferreira, email: carla.ssf@gmail.com, Phone.:
17 +351239802940, Fax: +351239802, Address: Escola Superior Agrária de Coimbra,
18 Bencanta, 3045-601 Coimbra, Portugal

19 **Email addresses of co-authors:** r.p.d.walsh@swansea.ac.uk, jpcn@ua.pt,

20 aferreira@esac.pt, r.a.shakesby@swansea.ac.uk, tammo@cornell.edu, coelho@ua.pt

21 ABSTRACT

22 Planning of semi-urban developments is often hindered by a lack of knowledge on how
23 changes in land-use affect catchment hydrological response. The temporal and spatial
24 patterns of overland flow source areas and their connectivity in the landscape, particularly
25 in a seasonal climate, remain comparatively poorly understood. This study investigates
26 seasonal variations in factors influencing runoff response to rainfall in a peri-urban
27 catchment in Portugal characterized by a mosaic of landscape units and a humid
28 Mediterranean climate. Variations in surface soil moisture, hydrophobicity and infiltration
29 capacity were measured in six different landscape units (defined by land-use on either
30 sandstone or limestone) in nine monitoring campaigns at key times over a one-year period.

31 Spatiotemporal patterns in overland flow mechanisms were found. Infiltration-excess
32 overland flow was generated in rainfalls during the dry summer season in woodland on
33 both sandstone and limestone and on agricultural soils on limestone due probably in large
34 part to soil hydrophobicity. In wet periods, saturation overland flow occurred on urban and
35 agricultural soils located in valley bottoms and on shallow soils upslope. Topography,
36 water table rise and soil depth determined the location and extent of saturated areas.
37 Overland flow generated in upslope source areas potentially can infiltrate in other
38 landscape units downslope where infiltration capacity exceeds rainfall intensity.
39 Hydrophilic urban and agricultural-sandstone soils were characterized by increased
40 infiltration capacity during dry periods, while forest soils provided potential sinks for
41 overland flow when hydrophilic in the winter wet season. Identifying the spatial and
42 temporal variability of overland flow sources and sinks is an important step in
43 understanding and modelling flow connectivity and catchment hydrologic response. Such

44 information is important for land managers in order to improve urban planning to minimize
45 flood risk.

46 **Keywords:** soil moisture, soil hydrophobicity, infiltration capacity, Mediterranean, spatial
47 and temporal variability, landscape units, overland flow, flow connectivity, urban
48 hydrology.

49

50 1. Introduction

51 Land-use changes associated with urbanization strongly affect hydrological processes.
52 Research into the hydrological effects of urbanization has focused on its impact on runoff
53 processes, but conclusions have proved difficult to extrapolate because of the complex
54 interplay of such parameters as climatic setting (Boyd et al., 1993; Costa et al., 2003),
55 geologically-controlled topography (Wilson et al., 2005), soil properties (López-Vicente et
56 al., 2009; Hardie et al., 2011), vegetation and land-use (Mallick et al., 2009), including
57 land-use change history, and the percentage of impervious surface and its spatial
58 arrangement (e.g. Konrad and Booth, 2005). Variation in the combined effect of these
59 factors is arguably the main reason for observed differences in impact of urban land-use
60 change on hydrology.

61 Soil moisture, linked to storage capacity, is recognized as a major runoff-controlling factor,
62 particularly in a Mediterranean climate (Cerdà, 1997). Its seasonal variability can mean that
63 greater rainfall intensity is required for overland flow initiation in summer than in winter
64 (Cammeraat, 2002). When saturation overland flow mechanisms are involved, the influence
65 of soil moisture is more varied and not entirely understood, particularly in urbanizing

66 catchments where its spatial and temporal variabilities are rarely reported (Easton et al.,
67 2007).

68 Although there have been many studies of soil hydrophobicity and its impacts on
69 infiltration and overland flow in a range of seasonal and sub-humid environments (e.g.
70 Glenn and Finley, 2010; Carrick et al., 2011; Orfánus et al., 2014), in areas of
71 Mediterranean climate they have mainly focussed on forested terrain (e.g. Doerr et al.,
72 1996, 1998, 2000; Varela et al., 2005; Keizer et al., 2008; Neris et al., 2013; Nyman et al.,
73 2014). Furthermore, relatively little is known about ‘switching’ between hydrophobic and
74 hydrophilic conditions in dry and wet periods respectively and the net effects on catchment
75 hydrological response in areas affected seasonally by soil hydrophobicity (Leighton-Boyce
76 et al., 2005). In hydrological modelling of urbanizing areas, the phenomenon has not even
77 been considered.

78 The seasonal and spatial variability of soil moisture and hydrophobicity on heterogeneous
79 landscapes affects overland flow sources and sinks, and is critical in understanding flow
80 transfer between different landscape units (Kirkby et al., 2002; Bull et al., 2003). Relatively
81 little research into such hydrological effects has been carried out in Mediterranean
82 environments, so the impact of marked seasonal changes on runoff processes is not well
83 understood. This is even truer of peri-urban areas, which represent the transition zone
84 between urban and rural environments on the outskirts of cities and which often comprise a
85 mosaic of land-use types. Here, better understanding of the interplay between these factors
86 would help in the prediction of the flow response and estimation of the overland flow
87 amount reaching any point in a catchment (Borselli et al., 2008).

88 This paper focuses on temporal and spatial variations in key soil hydrological properties
89 (soil moisture, hydrophobicity and infiltration capacity) in different land-uses in a small,
90 peri-urban, partly limestone, partly sandstone catchment in central Portugal. The catchment
91 has changed rapidly from agricultural land and forest to a discontinuous urban fabric, with
92 urban patches interrupting both woodland and semi-abandoned agricultural terrain. The
93 urban areas comprise a complex mosaic of tarmac, gardens and walls, in addition to
94 buildings and derelict ground. The distinctive mosaic pattern of the catchment is typical of
95 Portuguese urbanization. Specific aims of the paper are to: 1) assess spatial and temporal
96 variability of hydrological soil properties in different land-uses/lithology landscape units in
97 the catchment; 2) identify seasonal changes in overland flow sources; 3) evaluate the
98 impact of landscape units (characterized by different land-uses and lithologies) on flow
99 connectivity and streamflow response; and 4) explore implications of urbanizing mosaics
100 for landscape management and urban planning, especially with respect to streamflow
101 regimes and flood risk.

102

103 **2. Study area**

104 The study site is the S-N elongated *Ribeira dos Covões* catchment (40°13'N, 8°27'W; 6.2
105 km²) in the suburbs of Coimbra, the largest city of central Portugal. The climate (as
106 recorded at Bencanta, 0.5 km north of the catchment boundary) is humid Mediterranean,
107 with a mean annual temperature of 15°C, a mean annual rainfall of 892 mm (INMG, 1941-
108 2000), hot and dry summers (8% of rainfall in the months June-August) and wet winters
109 (Figure 1). The main watercourse is perennial, supplied by several springs, and there are
110 several smaller ephemeral tributaries (Figure 2). The geology (Figure 2a) comprises

111 Jurassic dolomitic and marly limestone in the east (49% of the catchment area), and
112 Cretaceous and Tertiary sandstones, conglomerates and mudstones in the west (47% of the
113 area), with some Pliocene-Quaternary sandy-conglomerate (colluvium) and alluvial
114 deposits (4% of the area) in the main valleys. Soils are generally deep (>3m) Cambisols and
115 Podzols (Tavares et al., 2012). Only on steeper slopes in the northwest is soil depth less
116 than 40 cm. Altitude ranges from 29m to 201m. The average slope is 9°, but a few slopes
117 reach up to 46°.

118 The catchment, totally rural until 1972, underwent discontinuous urbanization in 1973 -
119 1993, followed by urban consolidation after 1993 (Tavares et al., 2012). The agricultural
120 area, mainly olives and arable land, declined from 48% in 1958 to 4% of the catchment in
121 2009. Woodland increased from 46% to 66% over the same period, changing also in nature
122 from *Quercus suber* and mixed woodland to large commercial plantations of pine (*Pinus*
123 *pinaster*) and eucalypt (*Eucalyptus globulus*) (Tavares et al., 2012). Urban land-use
124 increased from 6% in 1958 to 30% in 2009 (Figure 2b), of which 14% comprised
125 impervious surfaces and 16% urban soil. The result was a mosaic of older urban cores, with
126 detached houses and gardens, and newer apartment blocks. There are also a few small
127 industrial premises, recreational areas and an enterprise park begun in 2009. Urban storm
128 runoff (from roofs, streets and concrete paved areas) is either piped to tributaries or flows
129 directly towards the stream network. Where urban buildings and derelict urban land are
130 surrounded by fields, however, stormwater is not controlled.

131

132 **3. Methodology**

133 **3.1 Research design**

134 A network of 31 representative sites was established in the catchment to assess
135 hydrological properties of the six different land-use/lithology combinations or “landscape
136 units” (Figure 2b). There were: 1) 11 sites in woodland, 9 being on sandstone (dominated
137 by eucalypt, pine and mixed deciduous forest), and 2 on limestone (in small areas of oak
138 and mixed deciduous woodland); 2) 11 sites on agricultural fields, including 5 on sandstone
139 (dominated by light grazing pasture, small olive groves and minor cultivated patches) and 6
140 on limestone (in olive groves and abandoned fields undergoing natural succession); and 3)
141 9 sites on uncultivated urban soil, 4 on sandstone (bare soil sites associated with
142 construction and open spaces with ground vegetation between houses) and 5 on limestone
143 (derelict spaces between houses and between houses and roads).

144 At each site, soil moisture content, hydrophobicity and soil matrix infiltration capacity were
145 monitored 9 times between September 2010 and June 2011, to cover a representative range
146 of antecedent weather and seasonal conditions, including prolonged periods of wet weather
147 and long dry spells. Temperature and rainfall data during the study period were provided by
148 the national meteorological weather station 12G/02UG, located at Bencanta, 0.5 km north
149 of the study catchment.

150 Replicate measurements of soil hydrological properties, spaced approximately 1m apart,
151 were carried out at each site. In total, 558 measurements of each parameter were obtained.
152 Three soil samples (c. 100 g each) were collected on the nine occasions at each site to
153 assess surface soil moisture (0-5 cm depth). Additional soil samples were taken at all sites
154 on 23rd November 2010 to determine dry bulk density, rock fragment content, organic
155 matter and particle size distribution. The excavation method (15×15 cm and 10 cm depth)
156 was used for bulk density and rock fragment analyses (three samples per location) (Dane

157 and Topp, 2002). Composite samples were also collected at depths of 0-5 cm and 5-10 cm
158 for organic matter and particle size distribution analyses. Each composite sample comprised
159 17 sub-samples collected at 15 cm intervals along a 2.4 m transect at each site.

160

161 **3.2 Field methods and procedure**

162 Soil matrix infiltration capacity was measured using a Minidisk Tension Infiltrometer
163 (Decagon Devices; 4.5 cm diameter and pressure head of -3.0 cm). Before measurements,
164 ground vegetation was trimmed and surface litter carefully removed. Following preliminary
165 trials, measurements were taken over 30 minutes by which time steady-state conditions
166 were assumed to have been reached. Unsaturated hydraulic conductivity was calculated
167 using published guidelines (Zhang, 1997; Li et al., 2005; Decagon, 2007). Infiltration
168 capacity, however, was calculated from the final 10 minutes of data (i.e. when the values
169 were judged to have stabilized). Taking all measurements as recommended by Decagon
170 (2007) would have given spurious values due both to initially high infiltration in
171 hydrophilic soils and to delayed infiltration when soils were hydrophobic.

172 Near each infiltrometer location, soil hydrophobicity was assessed at depths of 0, 2 and 5
173 cm using the Molarity of an Ethanol Droplet (MED) technique (Doerr et al., 1998). Fifteen
174 drops of distilled water and then progressively higher concentrations of ethanol were
175 applied until the lowest concentration was identified at which at least 8 out of 15 drops
176 were absorbed within 5 seconds. Ethanol concentrations of 0, 3, 5, 8.5, 13, 18, 24 and 36
177 percent by volume were used. The soil was considered wettable (hydrophilic) when
178 distilled water drops infiltrated within 5 seconds. The classes of levels of hydrophobicity

179 used were: low for 3 and 5% ethanol, moderate for 8.5 and 13%, severe for 18 and 24%,
180 and extreme for 36% (Doerr et al., 1998).

181

182 **3.3 Laboratory methods**

183 Soil physical properties (bulk density, rock fragment, organic matter content and particle
184 size) were analysed using standard methods (Dane and Topp, 2002). Bulk density was
185 obtained from undisturbed samples dried at 105°C. Disturbed soil samples were oven-dried
186 at 38 °C until a constant weight was reached, and the <2mm fraction extracted. The >2mm
187 rock fragment content was calculated as a percentage of the total dry soil sample weight.
188 The organic matter content was analyzed by oxidation at 600°C and detected by close infra-
189 red, using SC-144DR equipment (Strohlein Instruments). Porosity was calculated from the
190 dry bulk density and the organic matter content according to methods recommended by
191 Dane and Topp (2002), assuming a soil mineral particle density of 2.65 g cm⁻³ and organic
192 matter bulk density of 0.90 g cm⁻³. The particle size distribution of the minerogenic
193 component of the soil samples was determined where organic matter content was > 2%
194 either by: 1) oxidation using hydrogen peroxide (6%), for samples with organic matter
195 contents of 2-4%; or 2) heating to 550°C for samples with higher values. The samples were
196 then dispersed using Na-hexametaphosphate and the ultrasonic method (Dane and Topp,
197 2002). Particle size distribution was subsequently determined using a combination of
198 sieving, gravity sedimentation and pipette analysis. Soil texture classes were based on the
199 ISSS international classification (Soil Survey Division Staff, 1993).

200 Soil moisture content was assessed on each measurement occasion by the
201 thermogravimetric method following oven-drying at 105°C. Soil saturation was than
202 estimated by dividing the volumetric water content (estimated from gravimetric water
203 content and bulk density) by porosity.

204

205 **3.4 Data analysis**

206 The statistical significance of soil property differences between the land-use/lithology
207 landscape units was investigated first using the non-parametric Kruskal–Wallis H test
208 (SPSS 17.0). Where significant differences between units were identified, the Least
209 Significant Difference (LSD) Post-Hoc test was applied to identify distinct units or groups
210 of units. The same tests and procedure were applied to differences in soil hydrological
211 properties between measuring dates. A 95% level of significance ($p < 0.05$) was used. In
212 addition, Pearson-r correlation coefficients were calculated to assess linear relationships
213 between: 1) soil properties (organic matter content, bulk density and particle size) and soil
214 moisture, soil hydrophobicity and infiltration capacity ($n=64$); and 2) antecedent weather
215 and soil hydrological properties on each monitoring occasion. Principal Component
216 Analysis was used to quantify the infiltration variance explained by the correlated variables.
217 Although the data were not normally distributed, it was considered useful to apply this
218 technique for explorative purposes to improve understanding of the controls on overland
219 flow. Spatial patterns of hydrological soil properties were analyzed using geostatistical
220 methods, based on Thiessen Polygons, carried out using ArcGIS 9.3 software.

221

222 **4. Results and analysis**

223 **4.1 Soil properties**

224 Soil organic matter was generally higher and more consistent for surface (0-5 cm) than
225 subsurface soil (5-10 cm) (Figures 3a and 3b). For both soil depths, organic matter content
226 increased from urban (1-3%) to agricultural (3-9%) and woodland soils (averaging 7% and
227 14% on sandstone and limestone, respectively). In the woodland and agricultural-limestone
228 landscape units, organic matter was highly variable, but greater than in agricultural-
229 sandstone and urban soils ($p < 0.05$).

230 Bulk density increased from woodland (0.7 g cm^{-3}) to agricultural (1.0 g cm^{-3}) and to urban
231 soils (1.2 g cm^{-3}) (Figure 3c). In woodland and urban soils, bulk density was similar on
232 both lithologies ($p > 0.05$), but it was higher for agricultural-sandstone than agricultural-
233 limestone soils (median values of 1.1 g cm^{-3} and 0.9 g cm^{-3}) ($p < 0.05$). Values for the latter
234 were similar to woodland, whereas agricultural-sandstone values were similar to urban soils
235 ($p > 0.05$). Bulk density decreased with as soil organic matter increased ($r = -0.341$, $p < 0.001$).

236 Soil porosity ranged from 40 to 65% (Figure 3d) with generally lower values for urban
237 soils, despite no significant difference ($p > 0.05$). Greater heterogeneity was found for
238 agricultural soils, with higher values on limestone than sandstone ($p < 0.05$). Rock fragment
239 content ranged from 14 to 57% and was similar amongst landscape units ($p > 0.05$). Particle
240 size varied between individual sites (Figure 3e and 3f), but not between landscape unit
241 averages ($p > 0.05$), with sandy-loam and loamy-sand textures dominating. Particle size
242 distribution affected bulk density, which increased with larger coarse sand ($r = 0.189$,

243 p<0.001) and clay fractions ($r=0.115$, $p<0.001$), and diminished with larger fine sand ($r=-$
244 0.287 , $p<0.001$) and silt fractions ($r=-0.190$, $p<0.001$).

245

246 **4.2 Antecedent weather conditions**

247 Rainfall and temperature patterns during the monitoring period are shown in Figure 4 and
248 antecedent conditions for each measurement date are summarized in Table 1. Antecedent
249 30-day rainfall ranged from 5.0 mm (30/09/2010) to 141.8 mm (23/11/2010). Antecedent 5-
250 day rainfall ranged from rainless (prior to 30/09/2010 and 13/06/2011) or trace (0.2 mm
251 prior to 15/10/2010 and 24/01/2011) to 26.0 mm (prior to 03/01/2011) and 75.4 mm (prior
252 to 02/11/2010).

253

254 **4.3 Soil hydrophobicity**

255 Soil hydrophobicity varied greatly in severity and frequency both between landscape units
256 and with season and antecedent weather (Figures 5 and 6). Surface (0 cm) and subsurface
257 (2 cm and 5 cm) soil (results not shown) exhibited similar spatial and temporal trends.
258 Hydrophobicity increased with temperature ($r=0.337$, $p<0.001$) and decreased with
259 antecedent 2- and 30-day rainfall ($r=-0.298$ and -0.373 respectively, $p<0.001$). The area
260 affected by hydrophobicity was larger in summer (50% of all measurement sites) and
261 hydrophobicity was more severe in summer than in winter. It disappeared in late November
262 and January, except at woodland-sandstone sites (<20% of all sites).

263 Hydrophobicity was of greater severity and spatial extent in woodland, where after dry
264 spells it required several rainfall events to lessen its impact, particularly on sandstone
265 (Figures 5a and 5b). At agricultural sites especially on limestone (Figures 5c and 5d),
266 hydrophobicity was also present in dry periods but was less severe than on woodland and
267 rapidly decreased in percentage frequency following rainstorms and disappeared in wetter
268 periods. Urban soil was mostly hydrophilic (Figures 5e and 5f), with hydrophobicity only
269 affecting a minority of sites even in the driest periods. Re-establishment of hydrophobic
270 conditions in dry weather also varied with land-use, being rapid in woodland, particularly
271 on sandstone where it re-appeared by 24 January 2011, but far slower on agricultural and
272 urban soils, where it was absent until March 2011. Significant differences between
273 woodland and urban soils were found ($p < 0.05$).

274 A positive correlation was identified between hydrophobicity severity and organic matter
275 content ($r = 0.308$ for surface and 0.345 for subsurface soil, $p < 0.001$). Hydrophobicity was
276 correlated with particle size, increasing with surface fine sand ($r = 0.197$, $p < 0.001$) and
277 decreasing with subsurface clay fraction ($r = -0.226$, $p < 0.001$). This was reflected also in a
278 negative correlation with bulk density ($r = -0.240$, $p < 0.001$). Hydrophobicity was also found
279 to be inversely correlated with soil moisture ($r = -0.363$, $p < 0.001$, $n = 558$). Nevertheless,
280 hydrophilic conditions were recorded at least at some locations in all agricultural and urban
281 landscape units over the range of soil moisture contents recorded, whereas in woodland
282 soil was invariably hydrophobic at contents below 20%. There seemed to be no particular
283 moisture threshold, although at 75% of the measurement sites, at least low hydrophobicity
284 was characteristic below 45% soil moisture. Hydrophobicity, however, was recorded at a
285 few woodland sites with 70% soil moisture.

287 4.4 Soil moisture

288 Surface soil moisture varied with antecedent weather (Figures 7 and 8), increasing after
289 rainfall (although correlations were weak: $r=0.375$, 0.168 , 0.258 and 0.541 with 2-, 5-, 10-
290 and 30-day antecedent rainfall, respectively, $p<0.001$) and declining with higher
291 temperature ($r=-0.593$ with values in previous 5 days, $p<0.001$). During summer and after
292 long rain-free periods (30/09/2010 and 13/06/2011), soil became dry (<20% moisture)
293 across the catchment.

294 Land-uses responded differently to rainfall and limestone areas generally had higher soil
295 moisture than sandstone areas. This was very pronounced on 2nd November 2010 (Figure
296 7). Soil moisture was generally lower in urban sandstone soils throughout the year, but also
297 on woodland sandstone in winter and in dry-wet and wet-dry transition periods. Indeed, the
298 lowest post-summer (30/09/2010) median soil moisture content was recorded in woodland
299 sandstone areas, where it persisted until late autumn (23/11/2010). Conversely, agricultural
300 and urban limestone soils generally exhibited higher moisture contents, especially in the
301 wettest periods, when soil saturation occurred at a few valley-floor sites near streams
302 (Figure 8). Nevertheless, the locations and sizes of wettest areas in *Ribeira dos Covões*
303 changed through time, and high soil moisture values were recorded occasionally at a
304 minority of woodland sandstone sites in winter. In general, soil moisture content increased
305 with greater silt ($r=0.220$, $p<0.001$) and clay ($r=0.163$, $p<0.001$) fractions.

306

307 4.5 Infiltration capacity

308 Soil matrix infiltration capacity in the *Ribeira dos Covões* catchment was generally low,
309 despite occasional higher values (Figures 9 and 10). In general, sandstone soils recorded
310 greater permeability than limestone soils. Land-use also affected infiltration capacity but
311 differences varied with season and weather (Figure 9). Generally, woodland recorded
312 higher values in wet than dry periods ($p < 0.05$), with median values increasing from 0.1 -
313 0.2 mm h⁻¹ on 13/06/2011 and 30/09/2010 to 2.8 mm h⁻¹ on 03/01/2010. Nevertheless, after
314 the summer, higher infiltration capacity in woodland occurred earlier on limestone than
315 sandstone. Urban soils showed the opposite trend ($p < 0.05$), with median infiltration
316 capacity diminishing from 2.6 mm h⁻¹ on 13/06/2011 and 3.1 mm h⁻¹ on 30/09/2010 to 1.4
317 mm h⁻¹ on 03/01/2010, with slightly higher values on sandstone than on limestone. In
318 agricultural areas, the fall in median infiltration capacity (from 2.5 mm h⁻¹ on 30/09/2010 to
319 0.8 mm h⁻¹ on 03/01/2010) was not statistically significant.

320 Infiltration capacity increased with sand content ($r = 0.228$ and $r = 0.201$ for surface and
321 subsurface soil respectively, $p < 0.001$), but decreased with clay fraction ($r = -0.140$ for
322 subsurface soil, $p < 0.001$) and organic matter ($r = -0.149$, $p < 0.001$). Statistically significant
323 correlations were also found between infiltration capacity and hydrophobicity ($r = -0.314$
324 and -0.111 at 0 cm and 2 cm depth respectively, $p < 0.001$), as well as soil moisture ($r =$
325 0.117 , $p < 0.001$).

326 Generally, infiltration capacity was significantly correlated with hydrophobicity and soil
327 moisture, but the lower correlation coefficients may be because infiltration capacity was
328 only calculated during the last 10 minutes, and hydrophobicity and soil moisture were
329 measured separately on adjacent soil. Nevertheless, Principal Component Analysis (PCA)
330 showed that despite the complex interaction between hydrophobicity and soil moisture,

331 these variables together explain 63% of total infiltration capacity variance (Table 2). When
332 particle size characteristics (surface and subsurface coarse sand and silt fractions, and
333 subsurface clay) and organic matter content (surface and subsurface) are considered, the
334 three component variables together explain 76% of infiltration variance (Table 3).
335 However, the results of PCA must be interpreted as only indicative, since the variables do
336 not follow the normal distribution that is strictly required by the approach.

337

338 **5. Discussion**

339 **5.1 Characteristics of the landscape units and their influence on overland flow**

340 **5.1.1 Woodland landscape units**

341 Woodland environments showed the highest soil organic matter content over the catchment.
342 The high variability of this soil property within woodland areas may be due to differences
343 in tree species and management practices affecting the litter layer thickness. The lower
344 organic matter of eucalypt than other woodlands may reflect (a) periodic understorey
345 clearance to help prevent wildfires and (b) low understorey vegetation caused by reduced
346 water availability (DeBano, 2000). The generally low values of soil bulk density in
347 woodland units may be the outcome of higher organic matter in woodland soils than in soils
348 of the other landscape units and the denser root systems associated with a tree cover.
349 Reduced bulk density is also characteristic of soils with greater organic matter, since it
350 helps the formation of soil aggregates and structure (Celik et al., 2010).

351 The greatest soil hydrophobicity of woodland units can be linked to the species involved
352 and their organic matter produced. Seasonal changes in hydrophobicity, with high values in

353 summer and predominant disappearance in winter, was more pronounced in woodland than
354 other landscape units and is in accordance with previous studies (e.g. Dekker and Ritsema,
355 1994; Doerr et al., 2000; Martínez-Zavala and Jordán-López, 2009). Within woodland,
356 however, hydrophobicity was more extensive, severe and persistent in sites overlying
357 sandstone than limestone (Figures 5a and 5b) Thus in woodland-sandstone areas a larger
358 number of rainfall events was required for the soil to become hydrophilic, and even during
359 the wettest periods, hydrophobicity persisted at a few sites. This is probably because
360 sandstone areas are mainly dominated by eucalypt and pine plantations, whereas on
361 limestone, oak is more dominant. The types of resins, waxes and aromatic oils produced
362 by eucalypt (Doerr et al., 1998; Jordán et al., 2008) are thought to have caused
363 hydrophobicity to be more extensive and resilient than in the other woodland stands, with
364 hydrophobicity in eucalypt stands able to persist following rainfall of as much as 200 mm
365 in 2 months (Ferreira, 1996; Doerr and Thomas, 2000). In contrast, in woodland-limestone
366 areas, hydrophobicity was less severe and soil more easily switched to a hydrophilic state
367 because oak, which is not usually associated with hydrophobic soil (Zavala et al., 2009), is
368 the dominant vegetation.

369 Generally, woodland areas were also characterized by a more rapid re-establishment of
370 hydrophobic conditions after rainfall events compared with the other landscape units,
371 particularly in eucalypt plantations. The rate of re-establishment depends on the biological
372 productivity of the ecosystem (Doerr and Thomas, 2000; Hardie et al., 2012), the type of
373 hydrocarbon substances produced and microbial activity (Keizer et al., 2008). Santos et al.
374 (in press) also report greater dynamism and more frequent hydrophobic conditions in
375 eucalypt than in pine.

376 Nevertheless, differences in soil hydrophobicity between sandstone and limestone may
377 also be linked to differences in particle size, given the statistically significant (albeit weak)
378 positive correlation found between hydrophobicity and the sand fraction. This correlation
379 has also been recorded elsewhere (e.g. DeBano, 1991; McKissock et al., 2000), although a
380 few studies have reported hydrophobicity in relatively fine-textured soils (e.g. Doerr and
381 Thomas, 2000).

382 The higher evapotranspiration associated with a forest cover (e.g. Holden, 2008) may
383 explain the low soil moisture contents recorded during dry periods in woodland, compared
384 with the other land-uses (Figure 7), though shading by ground vegetation and litter can
385 reduce soil moisture loss in warm, sunny conditions. The more intense hydrophobic
386 conditions in eucalypt and pine woodland, by hindering infiltration (Dekker and Ritsema,
387 1994; Doerr and Thomas, 2000), might also help to explain the lower soil moisture results
388 recorded in woodland-sandstone compared with limestone at times of transition from dry to
389 wet conditions (15/10/2010 and 02/11/2011).

390 Despite the inverse correlation found between hydrophobicity and soil moisture content in
391 the woodland units, no soil moisture threshold seems to determine the switching pattern
392 between hydrophobic and hydrophilic soil properties. This accords with the inconsistent
393 results recorded elsewhere. Thus in field experiments in Portugal, Leighton-Boyce et al.
394 (2005) reported no threshold for up to 50% soil moisture content, whereas Doerr and
395 Thomas (2000) found one at 28%. Reports of thresholds outside Portugal vary from 21%
396 for medium-textured soils in SE Spain (Soto et al., 1994), to 38% for Dutch clayey peats
397 (Dekker and Ritsema, 1994) and 50% for some organic-rich Swedish soils (Berglund and
398 Persson, 1996).

399 The seasonal changes in soil hydrophobicity in woodland areas would explain the seasonal
400 contrast in infiltration capacity. Thus, in summer when the woodland soil was at its driest
401 and hydrophobicity was widespread, measured infiltration capacity was minimal, whereas
402 in wettest weather in winter, the limited spatial extent of hydrophobicity allowed
403 infiltration capacity to attain its highest values within *Ribeira dos Covões*. Nevertheless, the
404 low inverse correlation coefficient found between infiltration capacity and hydrophobicity,
405 despite being statistically significant, may have arisen because infiltration may sometimes
406 have been delayed by repellency, but on other occasions have commenced with switching
407 to hydrophilic conditions by the end of the final 10 minutes of the 30 minutes measurement
408 period.

409 Organic matter arguably plays a dual role in explaining the seasonal contrast in infiltration
410 capacity in woodland units. Thus, although it is associated with hydrophobic conditions and
411 low infiltration capacities in dry and transitional weather, in wet periods in winter, when
412 hydrophobicity has largely disappeared, the same high levels of organic matter promote
413 structured soils of high matrix infiltration capacity, representing the more typical situation
414 of forest soils (e.g. Costa, 1999; Mouri et al., 2011).

415 The variations in hydrophobicity, soil moisture and infiltration capacity linked to geological
416 and land-use controls and seasonal climatic influences discussed above result in
417 spatiotemporal patterns of overland flow that differ seasonally and between woodland-
418 sandstone and woodland-limestone areas. In storms following summer dry periods (e.g.
419 following 30/09/2010 and 13/06/2010), drought-induced hydrophobicity in eucalypt and
420 pine areas and the resulting very low matrix infiltration capacity make the woodland-
421 sandstone areas particularly susceptible to infiltration-excess overland flow generation. In

422 contrast, the less hydrophobic nature of the mainly oak vegetation of woodland-limestone
423 areas means that they are less prone to infiltration-excess overland flow. Prolonged or
424 repeated rainfall events led to partial switching of woodland soils to a hydrophilic state and
425 reductions in spatial extent and severity of hydrophobicity. Hydrophobicity in eucalypt
426 stands is more resistant to breakdown, requiring longer and/or a greater number of rainfall
427 events. Because of this, infiltration capacity generally remained low in woodland sandstone
428 areas (Figure 9a), and therefore prone to generate overland flow during transitions from dry
429 to wet conditions, as recorded on 15th October 2010. In prolonged wet weather of the winter
430 season, hydrophobicity largely disappeared even in woodland-sandstone areas, and no
431 infiltration-excess overland flow occurred. Even under the wettest winter conditions,
432 woodland areas showed relatively low soil moisture and high infiltration capacities and
433 saturation overland flow was rare.

434 The potential for infiltration-excess overland flow in woodland landscape units in dry
435 summer conditions was confirmed by rainfall simulation experiments, when a 43 mm h⁻¹
436 simulated rainfall produced runoff coefficients of 20-83% in a small plot (0.25 m²) in
437 extremely hydrophobic woodland soil (slope: 5-36°) (Ferreira et al., 2012b).

438 On larger runoff plots (16m²) in woodland, however, under extremely hydrophobic
439 conditions, overland flow did not exceed 3% even for a 23mm natural rainfall event
440 (Ferreira et al., 2012a), mainly because of infiltration bypassing the hydrophobic soil
441 matrix via macropores that can be provided by root-holes, invertebrate activity and high
442 concentrations of stones (e.g. Urbanek and Shakesby, 2009; Hardie et al., 2011). Such
443 bypass (preferential) flow is viewed as an important mechanism not only in extremely
444 hydrophobic soils (Doerr and Thomas, 2000), but also in dry loamy soils with high clay and

445 silt contents (Yang and Zhang, 2011; Bracken and Croke, 2007). Certainly, cracks in clay
446 soils were observed in dry conditions during fieldwork in the catchment study.

447

448 **5.1.2 Urban landscape units**

449 In contrast to woodland, areas of urban landscape units in the *Ribeira dos Covões*
450 catchment are characterized by the lowest soil organic matter content. This is probably
451 linked to the reduced and patchy vegetation cover and, in some locations, either loss or re-
452 deposition of surface soil. The higher bulk density may be largely due to compaction by
453 people and vehicles (Silva et al., 1997), as a result of vehicle access and parking in the
454 discontinuous urban fabric. Soil bulk densities measured ($1.07\text{-}1.72\text{ g cm}^{-3}$) were similar to
455 those ($1.19\text{-}1.62\text{ g cm}^{-3}$) reported in Nanjing, China, where lowest values were recorded in
456 greenbelt areas and highest in parking zones (Yang and Zhang, 2011).

457 In the *Ribeira dos Covões* catchment, the dominance of bare surfaces and sparse grass and
458 shrub vegetation is the main cause of the recorded widespread hydrophilic conditions
459 throughout the year. Only at particularly well vegetated sites was hydrophobicity recorded
460 during the driest periods. Bare soil sites, mainly found on sandstone, being more
461 susceptible to evaporation (Nunes et al., 2011), may have led to the low soil moisture
462 content recorded particular in dry-wet transitional periods, such as in the southwest of the
463 catchment on 02/11/2010 and 21/03/2011 (Figure 8).

464 The generally hydrophilic conditions found in urban soil would help to explain the high soil
465 matrix infiltration capacity values recorded particularly after prolonged dry weather (Figure
466 9), despite the high bulk density, which elsewhere has been noted to be associated with

467 lower infiltration capacities (e.g. Dornauf and Burghardt, 2000; Yang and Zhang, 2011).
468 The very low and in some cases zero values of soil matrix infiltration capacity recorded
469 during wet periods may be linked to a decline in the suction force and then saturation of the
470 soil. The inverse correlation recorded between soil moisture and infiltration capacity was
471 also found in Tasmania by Hardie et al. (2012), where the application of dye tracer showed
472 infiltration to an average depth of 1.03 m (with a wetting front velocity of 1160 mm h^{-1}) in
473 low antecedent soil moisture conditions, compared with a depth of 0.35 m (and a wetting
474 front velocity of 120 mm h^{-1}) with wet antecedent conditions.

475 In urban landscape units, overland flow is readily generated on impervious paved and
476 tarmac surfaces, but for urban soils it varies in importance both seasonally and between
477 urban-sandstone and urban-limestone areas. In dry summer conditions, the generally
478 hydrophilic soils of greater infiltration capacity (Figures 9 and 10) lead to little or no
479 overland flow and make these areas overland flow sinks. In contrast, after larger winter
480 storm events, soil saturation or near-saturation was identified at urban-limestone sites
481 (Figures 7 and 8) associated with a near-surface water table (on the valley floor) and
482 shallow soils of low water storage capacity (on hillslopes). In both situations, saturation
483 overland flow was at least being generated locally. In contrast, in urban soils on sandstone,
484 moisture levels recorded in winter were much lower than on limestone (Figure 7) and
485 infiltration capacities (Figure 9) varied from low (on bare soil) to relatively high (on
486 uncompacted, vegetated sites); the result was patchy Hortonian overland flow, mostly on
487 the bare soil areas, with some of the vegetated patches acting as overland flow sinks.

488 The potential for overland flow generation in urban soils was demonstrated by runoff
489 coefficients of 59-99% recorded on hydrophilic urban soils (slope: 6-30°) in 43 mm h⁻¹
490 rainfall simulations on small plots (0.25 m²) at the field sites, though it was unclear whether
491 the overland flow was infiltration-excess or saturation in nature (Ferreira et al., 2012b).

492

493 **5.1.3 Agricultural landscape units**

494 In agricultural landscape units, different land-use/land management types led to major
495 differences on surface cover and soil properties. The agricultural types on sandstone
496 (mainly pasture, small gardens and olive plantations) may explain the low organic matter
497 content and high bulk density results of that landscape unit compared with the agricultural-
498 limestone unit, where abandoned fields undergoing natural vegetation succession are
499 dominant. This greater vegetation cover with higher soil organic matter content for
500 agricultural-limestone would also explain the unit's enhanced spatial extent and severity of
501 hydrophobicity than on sandstone. Nevertheless, hydrophobicity at agricultural-limestone
502 sites was less severe than in woodland, and fewer rainfall events were required to
503 accomplish switching from hydrophobic to hydrophilic conditions, and hydrophobicity re-
504 establishment in wet to dry transitions was also slower than for woodland (Figure 5). In a
505 previous study of a partly urbanized Mediterranean catchment, Fernández and Ceballos
506 (2003) only recorded lower hydrophobicity persistence when conditions were changing
507 from dry to wet.

508 The generally higher soil moisture values of agricultural compared with other landscape
509 units, despite the absence of irrigation, may be explained by the lower vegetation cover of
510 the agricultural-limestone sites together with their low hydrophobicity, particularly when
511 compared with woodland. In addition, high surface roughness associated with tillage in
512 agricultural-sandstone fields may enhance surface water retention and lead to higher soil
513 moisture (Álvarez-Mozos et al., 2009), especially when compared with untilled urban soils.

514 Soil moisture, however, was slightly higher at agricultural-limestone than agricultural-
515 sandstone sites, despite most of the former being abandoned. This may be a consequence of
516 the marly nature of the limestone, resulting in a higher proportion of fine material.
517 However, the small soil moisture difference may reflect the fact that most sandstone
518 agricultural sites are on valley floors (Figure 8), and thus often generally moist, whereas
519 limestone sites are mainly on upper slopes, where the soil is shallow (generally <40 cm
520 depth) and often dry, though in the wettest periods some saturation was observed here.

521 Differences in particle size distribution and land management practices, particularly
522 wheeling, may explain higher soil porosity on abandoned limestone than on ploughed
523 sandstone fields. Nevertheless, a coarser particle size distribution and relatively weak
524 hydrophobicity may explain greater soil matrix infiltration capacity on sandstone compared
525 with limestone agricultural areas in dry periods.

526 Increasing soil moisture content during the wet season, however, could reduce soil matrix
527 infiltration capacity in agricultural areas, which was mostly apparent on sandstone fields. In
528 agricultural-limestone sites, matrix infiltration capacity was relatively constant during the
529 year. In this landscape unit, the slight infiltration capacity increase during early autumn,
530 possibly due to soil hydrophobicity reduction, gives way to a decreasing capacity in later

531 autumn and winter seasons, as a result of soil moisture increase. Throughout spring, with
532 soil moisture decreasing, infiltration capacity first tends to increase but later, possibly as a
533 result of hydrophobicity re-emergence at some sites, then reduces once more. The
534 development of hydrophobic conditions in the agricultural soils, however, was clearly
535 slower than in woodland (Figure 5).

536 In response to the contrasts in soil moisture, hydrophobicity and infiltration capacity and
537 their seasonal dynamics discussed above, overland flow generation varied between
538 agricultural-sandstone and agricultural-limestone landscape units. In the former, high
539 infiltration capacities associated with continuously hydrophilic sandy soils meant that
540 overland flow was absent in summer and in winter was only generated in big events or
541 following very wet weather. In contrast, the greater vegetation of the abandoned fields on
542 limestone led to hydrophobic soils in summer and a degree of proneness to infiltration-
543 excess overland flow. Despite partial switching in transition periods and total switching to
544 hydrophilic conditions in winter wet periods, the relatively low infiltration capacities and
545 high soil moisture resulting from the marly limestone lithology meant that the agricultural
546 limestone areas were more prone in winter to saturation overland flow than the sandstone
547 areas.

548 Unlike on urban and woodland soil sites, no infiltration-excess overland flow was recorded
549 in 43 mm h^{-1} rainfall simulation experiments on hydrophilic agricultural-sandstone land
550 (slope gradients, $15\text{-}40^\circ$) in the study area (Ferreira et al., 2012b).

551

552 **5.1.4 Synthesis: the influences of lithology, topography and land-use factors on**
553 **overland flow and temporal variation in its distribution within the *Ribeira dos Covões***
554 **catchment**

555 Lithology seems to play an important role in controlling spatiotemporal dynamics of
556 overland flow in the *Ribeira dos Covões* catchment via its influence on particle size
557 distribution, soil moisture and infiltration capacity variability over the catchment.
558 Generally, the greater sand fractions and deeper soils of the sandstone areas promote
559 greater infiltration capacity and water storage capacity, and lower soil moisture, leading to
560 reduced proneness to both Hortonian and saturation overland flow. In contrast, the higher
561 silt-clay content and shallower nature of soils on the marly limestone result in greater soil
562 moisture, lower infiltration and water storage capacities and hence greater proneness to
563 saturation overland flow than on sandstone, These effects are in line with reports
564 elsewhere of the influence on overland flow of shallow soils (Easton et al., 2007, Hardie et
565 al., 2011) and variations in particle size (Rahardjo et al., 2008; Yang and Zhang, 2011).

566 Local topographic characteristics represent a second important influence on overland flow
567 dynamics. Saturation was observed at urban soil sites near streams (Figure 8) caused either
568 by (1) lateral subsurface flows from upslope (Aryal et al., 2005) or (2) groundwater table
569 rise, as recorded at a woodland-sandstone site near to an active spring on 24th January 2011
570 (Figure 8). In a small cultivated Mediterranean catchment in the Pyrenees, Latron and
571 Gallart (2007) also related the saturation pattern to the extent and height of the water table.
572 The locations and extents of the wettest areas in the *Ribeira dos Covões* catchment varied
573 temporally, a feature also reported elsewhere within agricultural hillslope (Walter et al.,
574 2000) and mixed agricultural and forested (Easton et al., 2007) areas.

575 Land-use and land management constitute the third and perhaps most important influence
576 on differences in overland flow between and within landscape units. This influence is
577 exerted through the effects of different percentage ground covers, management practices
578 and other human activities on degrees of soil compaction, soil moisture levels and soil
579 permeability and via the effects of different plant species on hydrophobicity severity,
580 switching dynamics and seasonality. Overland flow is consequently of greatest
581 significance in urban landscape units, particularly in winter, when urban soils are often
582 either saturated or bare and compacted, whereas in summer overland flow from impervious
583 or bare areas is reduced by hydrophilic soil patches. Overland flow in the woodland units is
584 in general greatly reduced by vegetation effects on infiltration, but is seasonally enhanced
585 in storms following summer dry periods in eucalypt and pine woodland-sandstone areas
586 because of their severe soil hydrophobicity, but absent in woodland-limestone areas
587 because of the oak woodland land-use. The agricultural-sandstone landscape unit produces
588 very little overland flow because of high infiltration capacities resulting from a combination
589 of land-use and land management practices that do not result in compaction, but mostly
590 because of the sandy soils. In converse fashion, the abandoned field land-use of
591 agricultural-limestone areas probably has the effect of reducing overland flow responses
592 from what they would otherwise be with active cultivation, although for lithology-related
593 reasons responses can still be significant particularly in winter wet weather.

594 Differences in temporal variability of soil hydrological properties between landscape units
595 led to spatial fluctuation in overland flow sources and sinks. In wet winter conditions,
596 overland flow is greatest from the urban landscape units and also significant from the
597 agricultural-limestone unit, but comparatively little is generated on the hydrophilic and
598 permeable agricultural-sandstone and woodland units except in the wettest weather. During

599 transitions from wettest to dry conditions, the spatial pattern of response to rainstorms is
600 reversed, with decreasing susceptibility to saturation overland flow as soil moisture
601 declines (particularly in agricultural- and urban-limestone areas) and increasing
602 vulnerability to infiltration-excess overland flow, enhanced by hydrophobicity re-
603 establishment (particularly in woodland but also agricultural-limestone units). In summer,
604 overland flow is comparatively low but still greatest in urban-limestone areas and to a
605 lesser extent is also significant in the woodland and agricultural-limestone units because of
606 their hydrophobic condition, but urban-sandstone and agricultural-sandstone areas produce
607 comparatively little overland flow, because of at least locally hydrophilic and permeable
608 surface soils providing overland flow sinks. Finally, in the dry to wet transition of autumn,
609 patterns of overland flow are broadly similar to the wet-to-dry transition, with
610 hydrophobicity (and overland flow responses) becoming most rapidly re-established in
611 eucalypt areas of the woodland-sandstone landscape unit.

612 Spatial variability of soil properties *within* the same landscape unit, such as particle size
613 and hydrophobicity, provides heterogeneous infiltration capacities, where this particularly
614 applies to (a) the partly bare urban-sandstone unit and (b) the woodland and agricultural-
615 limestone units in transitional periods (Figure 9). Soil spots with matrix infiltration capacity
616 lower than rainfall intensity will lead to local infiltration-excess overland flow, which may
617 be infiltrated in surrounding soil spots of greater infiltration capacity. Not all landscape
618 units provided spots with sufficient permeability throughout the year. Urban and
619 agricultural landscape units showed more sites of high permeability after dry periods, while
620 even in the wettest conditions, woodland provided sites of high infiltration capacity.
621 Nevertheless, even the most permeable soil patches could not cope with the maximum
622 rainfall intensity of 15.6 mm h^{-1} recorded in the rainstorm of 2nd November 2011. Thus

623 infiltration-excess overland flow would be expected to occur widely during particularly
624 intense storms in all landscape units.

625

626 **5.2 Implications for catchment runoff delivery and land management**

627 The changing nature of overland flow sources and sinks within the catchment can be
628 expected to affect flow connectivity over the hillslope and influence storm runoff delivery
629 to the stream network. Under hydrophobic conditions, infiltration-excess overland flow
630 generated in relatively extensive woodland on steep slopes and on shallow upstream
631 agricultural-limestone soils, may reach the stream network directly or be delivered to the
632 urban cores situated downslope (Figure 2b).

633 Vegetation is widely considered as a key factor interrupting hydrological connectivity (e.g.
634 Bracken and Croke, 2007; Appels et al., 2011). Greater vegetation interception provided by
635 woodland and agricultural-limestone areas, compared with the other land-uses, tends to
636 reduce overland flow, though the effect will be marginal in large storm events, when
637 percentage interception is small. The more important effect of interception is in helping
638 (together with transpiration) to reduce antecedent soil moisture levels prior to rainfall
639 events. In central Portugal, Valente et al. (1997) reported relatively high interception losses
640 of 17% in *Pinus pinaster* forest and 11% in eucalypt stands and attributed them to the
641 greater canopy storage and, aerodynamic roughness (and hence higher evaporation rates)
642 of forest covers. In addition, greater litter density and frequency of root holes compared
643 with the other landscape units may lead to enhanced water interception, retention and
644 infiltration, particularly in smaller storm events after dry spells. Surface roughness also
645 enhances water retention and reduces overland flow rates, and promotes discontinuities

646 between overland flow source areas (Rodríguez-Caballero et al., 2012). These
647 infiltration/retention processes operating at larger scales, as well as preferential flow via
648 root-holes and cracks, considerably reduce the risk that overland flow from low permeable
649 soil sites might reach downslope contiguous urban areas and/or the stream network.
650 Although urban soils may provide overland flow sinks, the impermeable tarmac and paved
651 surfaces allow little infiltration, restricting the capacity of these areas to deal with rainfall
652 and overland flow from upslope landscape units. Observations in *Ribeira dos Covões* over
653 three years suggest that only small amounts of overland flow were generated in woodland
654 and agricultural limestone areas, mainly after dry conditions. Nevertheless, preferential
655 flow via macropores can reach streams relatively quickly and thus contribute to the flood
656 peak, as reported in other areas of the world (Uchida et al., 1999; van Schaik et al., 2008;
657 Yu et al., 2014).

658 Although not recorded during this study, clear-felling in woodland would cause increased
659 overland flow and water connectivity by providing bare, compacted areas and reducing
660 interception, transpiration and surface roughness. Thus the size and location of clear-felled
661 areas require planning to ensure that most overland flow is intercepted by downslope
662 woodland area sinks in order to reduce flood hazard. Clear-felling should also be timed to
663 avoid storms of early autumn rainy seasons, in view of the greater extent and location of
664 hydrophobic areas at that time (Figure 6). In addition, if forest managers select tree species
665 that release less hydrophobic substances, overland flow may be correspondingly reduced
666 (e.g. Ferreira et al., 2012a).

667 Under wet winter conditions, saturation overland flow becomes more likely in urban and
668 agricultural land-uses, but saturated areas may be more influenced by topography and soil

669 depth than by land-use (Figure 8). Overland flow generated in these landscape units would
670 be delivered mostly to the stream network, but also to downslope woodland and urban
671 cores in the case of upslope saturated shallow soils (Figures 2b and 8). Previous studies
672 reported higher runoff coefficients in shallow soils affecting hillslope runoff connectivity
673 (Kirkby et al., 2002; Easton et al., 2007; Hopp and McDonnell, 2009). In agricultural areas,
674 however, overland flow paths would depend on land management. Land drains, ditches,
675 wheel ruts and roads may enhance flow connectivity, particularly if they are aligned
676 downslope, whereas terracing and stone boundary walls can form traps for water,
677 enhancing infiltration and disrupting flow pathways. Overland flow transfer from
678 agricultural and urban areas to downslope woodland soils when hydrophilic may be
679 dissipated by enhanced infiltration and surface retention. Furthermore, although much of
680 the overland flow from impermeable urban surfaces located in upslope positions (Figure
681 2b) is collected by the urban drainage system and delivered directly into the stream, some
682 reaches nearby soil.

683 Because of the generally low infiltration capacity or saturated condition of downslope
684 urban soil areas, saturation overland flow reaching such areas may be problematic, although
685 this can be offset by spatial differences in modified and unmodified soil properties
686 providing a mosaic of different infiltration capacities. Even if urban soils surrounding
687 impermeable surfaces (e.g. roofs and roads) cannot act as sinks, obstructions (such as
688 buildings and walls) may delay overland flow transfer. This will depend on urbanization
689 style, since extended impermeable surfaces will enhance landscape connectivity, whereas
690 detached houses surrounded by gardens and walls can provide sinks and flow discontinuity.

691 The susceptibility of urban core areas located in topographic lows (Figure 2b) to saturation
692 overland flow and stream flooding may represent a real flood hazard for the inhabitants,
693 particularly considering the scale of recent urban consolidation in the *Ribeira dos Covões*
694 catchment. This risk may be enhanced by 1) additional overland flow resulting from greater
695 connectivity with upslope areas subject to soil moisture increase and water table rise, and 2)
696 the rapid transfer of most overland flow from upslope impermeable surfaces directly into
697 the stream via the urban drainage system. These may be particularly important in larger
698 storm events, considering the generally low soil permeability across the catchment.
699 According to interviews with older citizens, flooding events were already experienced
700 about 80, 50 and 10 years ago, when the urban area was considerably less extensive than
701 now.

702 Analyses of storm hydrographs of the outlet stream (results not shown) suggest that the
703 actual landscape mosaic of *Ribeira dos Covões* catchment, comprising extensive woodland
704 areas and large urban areas near the catchment outlet, together with numerous smaller
705 urban areas mainly along ridges and dispersed agricultural fields (Figure 2b), may be
706 sufficient to promote discontinuities to the infiltration-excess overland flow generated by
707 soil hydrophobicity. Thus, in dry settings, rainstorms of 2.8 mm (average) and 14.4 mm
708 (large), recorded on 6th August and 1st September 2011, promoted runoff coefficients for
709 the *Ribeira dos Covões* stream of only 5% and 2% respectively and peak streamflows of
710 only 0.041 mm h⁻¹ and 0.036 mm h⁻¹, compared with maximum 5-minute rainfall intensities
711 of 2.4 mm h⁻¹ and 9.6 mm h⁻¹ respectively. Thus, hydrophobicity over the catchment does
712 not translate into catchment-scale overland flow, presumably due to infiltration into sinks
713 downslope. In wet conditions, however, enhanced soil moisture levels seem to increase
714 flow connectivity over the catchment. Thus rainstorms of 2.8 mm and 15.0 mm registered

715 on 11th February and 28th March 2011, led to 10% and 9% storm runoff coefficients and
716 peak flows of 0.079 and 0.370 mm h⁻¹, compared with maximum rainfall intensities of 9.6
717 mm h⁻¹ in both cases. Although lag times from peak rainfall to peak streamflow are short,
718 ranging between 25 and 35 minutes, and probably a direct result of urban surface runoff
719 and the urban drainage system, the overriding feature is the small size of the storm runoff
720 coefficients both during dry and wet times of the year, which shows how little of the rain
721 falling on the peri-urban mosaic actually reaches the stream network. This may reflect in
722 part the ridge location of much of the urban expansion to date and in part a rather high
723 proportion of infiltration into urban soil within the urban units and adjacent landscape units.

724 The short lag times between rainfall and streamflow peaks in urban areas, however, mean
725 that future urban consolidation and the construction of new urban cores, already proposed,
726 must be planned carefully in order to minimize urban flood hazard. From the hydrological
727 point of view, instead of extending the existing urban cores, it would be better to establish
728 new dispersed urban cores far from the stream network. The maintenance of a patchy
729 mosaic of dispersed landscape units would reduce overland flow and river flood peak
730 responses.

731

732 **5 Conclusions**

733 The peri-urban *Ribeira dos Covões* catchment is covered by soils of relatively low matrix
734 infiltration capacity, but of greater permeability on sandstone than limestone, due to the
735 marly nature of the latter. The different landscape units, associated with different land-uses
736 and lithologies, display varying responses of soil hydrological properties to season and to

737 antecedent rainfall with complex consequences for spatial patterns of overland flow and its
738 flow connectivity. The main findings are:

739 1) In dry conditions, severe hydrophobicity in eucalypt and pine (but not oak)
740 woodland and limestone-agricultural areas (abandoned fields) considerably reduces
741 soil matrix infiltration capacity. In contrast, agricultural-sandstone soils (mainly
742 covered by olives, pasture and gardens) and urban soils remain mostly hydrophilic,
743 and have relatively high infiltration capacities. Under wet conditions,
744 hydrophobicity in woodland and agricultural-limestone areas breaks down and
745 infiltration capacity increases, reaching 6 mm h^{-1} . In contrast, on urban and
746 agricultural sites, a rise in soil moisture leads to a decline in infiltration capacity,
747 with soil saturation in areas of shallow soils and high water tables on hillslopes, in
748 topographic lows and in valley bottoms.

749 2) Temporal variability of soil hydrological properties indicates that, in dry conditions,
750 hydrophobicity-related infiltration-excess overland flow may be generated in
751 woodland and agricultural-limestone areas, while in wet conditions saturation is
752 likely in some locations on urban and agricultural soils. Nevertheless, soil property
753 heterogeneity and the distinct temporal pattern of infiltration capacity indicate that
754 much overland flow must be infiltrating before reaching the stream network in
755 patches of unsaturated soil of relatively high permeability, either within the same
756 landscape unit or on adjacent landscape units.

757 3) Despite the generally low soil matrix infiltration capacity across the catchment,
758 macropores, vegetation, litter and surface roughness play important roles in surface
759 water retention and facilitating infiltration. Nevertheless, these processes are
760 influenced by the different landscape units, which provide overland flow sinks with
761 differing temporal regimes. Because of this, a patchy mosaic comprising fragmented
762 and dispersed land-uses, and the tendency for much of recent urbanization to have
763 occurred along ridges, have to date led to relatively low flow connectivity over
764 hillslopes, thereby attenuating river discharge peaks.

765 Understanding how the spatial and temporal variability in overland flow generation and
766 infiltration affect flow connectivity in a catchment with varied land-use, geology and soils
767 is vital for predicting flood hazards. Landscape managers and urban planners should
768 employ a mosaic of different land-uses, where impermeable surfaces are joined
769 hydrologically to infiltration-promoting “green” areas, in order to prevent or reduce
770 downstream flooding. There need to be informed decisions about the precise spatial
771 arrangement of different land-uses.

772

773 **6 Acknowledgements**

774 This study was supported by PhD scholarship SFRH/BD/64493/2009 of the Portuguese
775 Science and Technology Foundation (FCT), under QREN – POPH – 4.1 Advanced
776 Training Typology, co-funding by European Social Fund and MEC national funds, and
777 FRURB project “Managing Flood Risk in Urban areas in a global change context”

778 (PTDC/AUR-URB/123089/2010) founded by FCT. The authors would like to thank the
779 Soil and Fertility laboratory of ESAC. We are grateful to Tanya Esteves for ArcGIS
780 support, and to Daniel Soares and Célia Bento for occasional fieldwork assistance.

781

782 **7 References**

783 Álvarez-Mozos, J., Verhoest, N.E.C., Larrañaga, A., Casali, J., González-Audícana, M.,
784 2009. Influence of Surface Roughness Spatial Variability and Temporal Dynamics on the
785 Retrieval of Soil Moisture from SAR Observations. *Sensors* 9(1), 463-489.

786 Appels, W.M., Bogaart, P.W., van der Zee, S.E.A.T.M., 2011. Influence of spatial
787 variations of microtopography and infiltration on surface runoff and field scale hydrological
788 connectivity. *Adv. Water Resour.* 34, 303–313.

789 Aryal, S.K., O., Loughlin, E.M., Mein, R.G. A., 2005. Similarity approach to determine
790 response times to steady-state saturation in landscapes. *Adv. Water Resour.* 28, 99-115.

791 Berglund, K., Persson, L., 1996. Water repellence of cultivated organic soils. *Acta*
792 *Agriculturae Sacandinavica Section B Soil and Plant Science* 46, 145-152.

793 Borselli, L., Cassi, P., Torri, D., 2008. Prolegomena to sediment and flow connectivity in
794 the landscape: A GIS and field numerical assessment. *Catena.* 75, 268–277.

795 Boyd, M. J., Bufill, M. C., Dnee, R. M., 1993. Pervious and impervious runoff in urban
796 catchments. *Hydrological Sciences.* 38, 463-478.

797 Bracken, L.J., Croke, J., 2007. The concept of hydrological connectivity and its
798 contribution to understanding runoff-dominated geomorphic systems. *Hydrol. Process.* 21,
799 1749–1763.

800 Bull, L.J., Kirkby, M.J., Shannon, J., Dunsford, H.D., 2003. Predicting hydrologically
801 similar surfaces (HYSS) in semi-arid environments. *Adv. Env. Monit. Mod.* 2, 1–13.

802 Cammeraat, L.H., 2002. A review of two strongly contrasting geomorphological systems
803 within the context of scale. *Earth Surf. Proc. Landf.* 27, 1201–1222.

804 Carrick, S., Buchan, G., Almond, P., Smith, N., 2011. Atypical early-time infiltration into a
805 structured soil near field capacity: The dynamic interplay between sorptivity,
806 hydrophobicity, and air encapsulation. *Geoderma.* 160, 579-589.

807 Cerdà, A., 1997. Seasonal changes of the infiltration rates in a Mediterranean scrubland on
808 limestone. *J. Hydrol.* 198, 209–225.

809 Celik, I., Gunal, H., Budak, M., Akpinar, C., 2010. Effects of long-term organic and
810 mineral fertilizers on bulk density and penetration resistance in semi-arid Mediterranean
811 soil conditions. *Geoderma* 160, 236–243.

812 Costa, J.B., 1999. *Caracterização e constituição do solo*, 6ª edição. Fundação Calouste
813 Gulbenkian, Lisboa.

814 Costa, M.H., Botta, A., Cardille, J.A., 2003. Effects of large-scale changes in land cover on
815 the discharge of the Tocantins River, Southeastern Amazonia. *J. Hydrol.* 283, 206–217.

816 Dane, J.H., Topp, C., 2002. *Methods of Soil Analysis, Part 4 – Physical Methods*. Soil
817 Science Society of America Book Series, Wisconsin, USA.

818 DeBano, L.F., 1991. The effect of fire on soil properties. US Department of Agriculture,
819 Forest Service General Technical Report. INT-280.

820 DeBano, L.F., 2000. Water repellency in soils: a historical overview. *J. Hydrol.* 231-232, 4-
821 32.

822 Decagon, 2007. Mini-infiltrometer manual, Version 4. Decagon Devices Inc., Pullman,
823 WA.

824 Dekker, L.W., Ritsema, C.J., 1994. How water moves in a water repellent sandy soil. I.
825 Potential and actual water repellency. *Water Resour. Res.* 30, 2507–2517.

826 Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., 1998. Spatial variability of soil
827 hydrophobicity in fire-prone eucalyptus and pine forests, Portugal. *Soil Sci.* 163, 313–324.

828 Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., 2000. Soil water repellency, its causes,
829 characteristics and hydro-geomorphological significance. *Earth-Sci. Rev.* 51, 33-65.

830 Doerr, S.H., Thomas, A.D., 2000. The role of soil moisture in controlling water repellency,
831 new evidence from forest soils in Portugal. *J. Hydrol.* 231-232, 134–147.

832 Dornauf, C., Burghardt, W., 2000. The effects of biopores on permeability and storm
833 infiltration – case study of the construction of a school. In, Burghardt, W., Dornayf, C.
834 (eds) First International conference on soils of urban, industrial, traffic and mining areas.
835 University of Essens, Essen, pp. 459-464.

836 Easton, Z.M., Gérard-Marchant, P., Walter, M.T., Petrovic, A.M., Steenhuis, T.S., 2007.
837 Hydrologic assessment of an urban variable source watershed in the Northeast United
838 States. *Water Resour. Res.* 43, W03413.

839 Fernández, J.M., Ceballos, A., 2003. Temporal stability of soil moisture in a large-field
840 experiment in Spain. *Soil Sci. Soc. Am. J.* 67, 1647–1656.

841 Ferreira, C.S.S., Soares, D., Ferreira, A.J.D., Coelho, C.O.A., Steenhuis, T.S., Keizer, J.J.,
842 Walsh, R.P.D., 2012a. The role of forest in runoff generation in a suburban catchment.
843 European Geoscience Union General Assembly, 22-27 April, Vienna, Austria. 14, 1014.

844 Ferreira, C.S.S., Ferreira, A.J.D., Pato, R.L., Magalhães, M.C., Coelho, C.O., Santos, C.,
845 2012b. Rainfall-runoff-erosion relationships study for different land-uses, in a sub-urban
846 area. *Z. Geomorphol.* 56(3), 5-20.

847 Ferreira, A.J.D., 1996. Processos hidrológicos e hidroquímicos em povoamentos de
848 *Eucalyptus globulus Labill.* e *Pinus pinaster Aiton*. PhDThesis, Departamento de Ambiente
849 e Ordenamento, Universidade de Aveiro, Portugal.

850 Glenn, N.F., Finley, C.D., 2010. Fire and vegetation type effects on soil hydrophobicity and
851 infiltration in the sagebrush-steppe: I. Field analysis. *J. Arid Environ.* 74, 653-659.

852 Hardie, M.A., Cotching, W. E., Doyle, R.B., Holz, G., Lisson, S., Mattern, K., 2011. Effect
853 of antecedent soil moisture on preferential flow in a texture-contrast soil. *J. Hydrol.* 398,
854 191–201.

855 Hardie, M.A., Doyle, R.B., Cotching, W. E., Mattern, K., Lisson, S., 2012. Influence of
856 antecedent soil moisture on hydraulic conductivity in a series of texture-contrast soils.
857 *Hydrol. Process.* 26, 3079–3091.

858 Holden, J., 2008. *An Introduction to Physical Geography and the Environment*. 2nd Edition,
859 ISBN-10, 0131753045.

860 Hopp, L., McDonnell, J.J., 2009. Connectivity at the hillslope scale, identifying interactions
861 between storm size, bedrock permeability, slope angle and soil depth. *J. Hydrol.* 376, 378–
862 391.

863 INMG, Instituto Nacional de Meteorologia e Geofísica, 1941-2000. Anuário climatológico
864 de Portugal. I Parte, Continente, Açores e Madeira – Observações de superfície. Lisboa.

865 Jordán, A., Martínez-Zavala, L., Bellinfante, N., 2008. Heterogeneity in soil hydrological
866 response from different land cover types in southern Spain. *Catena* 74, 137–143.

867 Keizer, J.J., Doerr, S.H., Malvar, M.C., Ferreira, A.J.D., Pereira, V.M.F.G., 2008.
868 Temporal and spatial variations in topsoil water repellency throughout a crop-rotation cycle
869 on sandy soil in north-central Portugal. *Hydrol. Process.* 21, 2317–2324.

870 Kirkby, M., Bracken, L., Reaney, S., 2002. The influence of land-use, soils and topography
871 on the delivery of hillslope runoff to channels in SE Spain. *Earth Surf. Proc. Land.* 27,
872 1459–1473.

873 Konrad, C.P., Booth, D.B., 2005. Hydrologic changes in urban streams and their ecological
874 significance. In, *Effects of urbanization on stream ecosystems.* (Eds. L.R. Brown, R.H.
875 Gray, R.M. Hughes & M.R. Meador), *American Fisheries Society Symposium.* 47, 157-
876 177.

877 Latron, J., Gallart, F., 2007. Seasonal dynamics of runoff-contributing areas in a small
878 mediterranean research catchment (Vallcebre, Eastern Pyrenees). *J. Hydrol.* 335, 194– 206.

879 Leighton-Boyce, G., Shakesby, R.A., Doerr, S.H., Walsh, R.P.D., Ferreira, A.J.D., Boulet,
880 A.K., Coelho C.O.A., 2005. Temporal dynamics of water repellency and soil moisture in
881 eucalypt plantations, Portugal. *Aust. J. Soil Res.* 43, 269-280.

882 Li, X.Y., González, A., Solé-Benet, A., 2005. Laboratory methods for the estimation of
883 infiltration capacity of soil crusts in the Tabernas Desert badlands. *Catena.* 60, 255–266.

884 López-Vicente, M., Poesen, J., Navas, A., Gaspar, L., 2013. Predicting runoff and sediment
885 connectivity and soil erosion by water for different land-use scenarios in the Spanish Pre-
886 Pyrenees. *Catena.* 102, 62–73.

887 Mallick, K., Bhattacharya, B.K., Patel, N.K., 2009. Estimating volumetric surface moisture
888 content for cropped soils using a soil wetness index based on surface temperature and
889 NDVI. *Agr. Forest Meteorol.* 149, 1327–1342.

890 Martínez-Zavala, L., Jordán-López, A., 2009. Influence of different plant species on water
891 repellency in Mediterranean heathland soils. *Catena.* 76, 215–223.

892 McKissock, I., Walker, E.L., Gilkes, R.J., Carter, D.J., 2000. The influence of clay type on
893 reduction of water repellency by applied clays, a review of some West Australian work. *J.*
894 *Hydrol.* 231, 323–332.

895 Mouri, G., Kanae, S., Oki, T., 2011. Long-term changes in flood event patterns due to
896 changes in hydrological distribution parameters in a rural–urban catchment, Shikoku,
897 Japan. *Atmos. Res.* 101, 164–177.

898 Neris, J., Tejedor, M., Rodríguez, M., Fuentes, J., Jiménez, C., 2013. Effect of forest floor
899 characteristics on water repellency, infiltration, runoff and soil loss in Andisols of Tenerife
900 (Canary Islands, Spain). *Catena* 108, 50-57.

901 Nunes, A.N., Almeida, A.C., Coelho, C.O.A., 2011. Impacts of land-use and cover type on
902 runoff and soil erosion in a marginal area of Portugal. *Appl. Geog.* 31, 687-699.

903 Nyman, P., Sheridan, G.J., Smith, H.G., Lane, P.N.J., 2014. Modeling the effects of surface
904 storage, macropore flow and water repellency on infiltration after wildfire. *J. Hydrol.* (in
905 press).

906 Orfánus, T., Dlapa, P., Fodor, N., Rajkai, K., Sándor, R., Nováková, K., 2014. How severe
907 and subcritical water repellency determines the seasonal infiltration in natural and
908 cultivated sandy soils. *Soil & Till. Res.* 135, 49-59.

909 Rahardjo, H., Indrawan, I.G.B., Leong, E.C., Yong, W.K., 2008. Effects of coarse-grained
910 material on hydraulic properties and shear strength of top soil. *Eng. Geol.* 101, 165–173.

911 Rodríguez-Caballero, E., Cantón, Y., Chamizo, S., Afana, A., Solé-Benet, A., 2012. Effects
912 of biological soil crusts on surface roughness and implications for runoff and erosion.
913 *Geomorphology* 145-146, 81–89.

914 Santos J.M., Verheijen F.G.A., Tavares Wahren F., Wahren A., Feger K.-H., Bernard-
915 Jannin L., Rial-Rivas M.E., Keizer J.J., Nunes J.P. In press. Soil water repellency dynamics
916 in pine and eucalypt plantations in Portugal - a high-resolution time series. *Land*
917 *Degradation and Development*, in press. DOI: 10.1002/ldr.2251.

918 Silva, A.P., Kay, B.D., Perfect, E., 1997. Management versus inherent soil properties
919 effects on bulk density and relative compaction. *Soil Till. Res.* 44, 81-93.

920 Soil Survey Division Staff, 1993. *Soil survey manual*. Soil Conservation Service. U.S.
921 Department of Agriculture Handbook 18.

922 Soto, B., Basanta, R., Benito, E., Perez, R., Diaz-Fierros, F., 1994. Runoff and erosion from
923 burnet soils in northwest Spain. In: Sala M., Rubio J.L. (Eds) *Soil Erosion as a*
924 *Consequence of Forest Fires*. Geofoma Ediciones, Logroño, pp.91-98.

925 Tavares, A.O., Pato, R.L., Magalhães, M.C., 2012. Spatial and temporal land-use change
926 and occupation over the last half century in a peri-urban area. *Appl. Geog.* 34, 432-444.

927 Uchida, T., Kosugi, K., Miizuyama, T., 1999. Runoff characteristics of pipeflow and effects
928 of pipeflow on rainfall-runoff phenomena in a mountainous watershed. *J. Hydrol.* 222(1-4),
929 18-36.

930 Urbanek, E., Shakesby, R.A., 2009. The impact of stone content on water flow in water-
931 repellent sand. *Eur. J. Soil Sci.* 60, 412-419.

932 Valente, F., David, J.S., and Gash, J.H.C., 1997. Modelling interception loss for two sparse
933 eucalypt and pine forests in central Portugal using reformulated Rutter and Gash analytical
934 models. *J. Hydrol.* 190, 141–162.

935 van Schaik, N.L.M.B., Schnabel, S., Jetten, V.G., 2008. The influence of preferential flow
936 on hillslope hydrology in a semi-arid watershed (in the Spanish Dehesas). *Hydrol. Process.*
937 22(18), 3844-3855.

938 Varela, M.E., Benito, E., de Blas, E., 2005. Impact of wildfires on surface water repellency
939 in soils of northwest Spain. *Hydrol. Process.* 19, 3649–3657.

940 Walter, M.T., Walter, M.F., Brooks, E.S., Steenhuis, T.S., Boll, J., Weiler, K.R., 2000.
941 Hydrologically sensitive areas, variable source area hydrology implications for water
942 quality risk assessment. *J. Soil Water Conserv.* 3, 277-284.

943 Wilson, D.J., Western, A.W., Grayson, R.B., 2005. A terrain and data-based method for
944 generating the spatial distribution of soil moisture. *Adv. Water Resour.* 28, 43–54

945 Yang, J.L., Zhang, G.L., 2011. Water infiltration in urban soils and its effects on the
946 quantity and quality of runoff. *J. Soils Sediment.* 11, 751–761.

947 Yu, X., Duffy, C., Baldwin, D.C., Lin, H., 2014. The role of macropores and multi-
948 resolution soil survey datasets for distributed surface-subsurface flow modeling. *J. Hydrol.*
949 in press. Doi, <http://dx.doi.org/10.1016/j.jhydrol.2014.02.055>.

950 Zavala, L., González, F.A., Jordán, A., 2009. Intensity and persistence of water repellency
951 in relation to vegetation types and soil parameters in Mediterranean SW Spain. *Geoderma*
952 152, 361–374.

953 Zhang, R., 1997. Determination of soil sorptivity and hydraulic conductivity from the disk
954 infiltrometer. *Soil Sci. Soc. Am. J.* 61, 1024–1030.

955

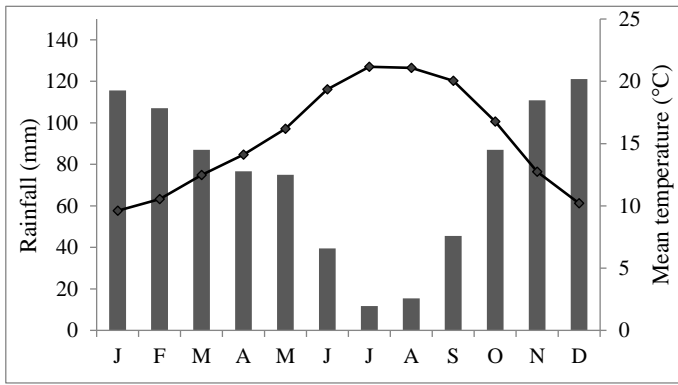


Figure 1 – Average monthly rainfall and temperature at Coimbra (Bencanta weather station), calculated from data regarding to the period 1941-2000 (INMG, 1941-2000).

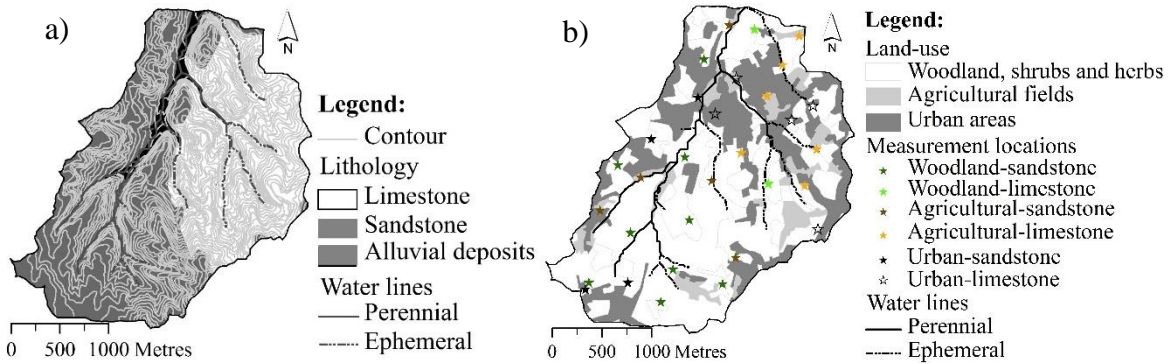


Figure 2 – Ribeira dos Covões catchment: (a) topography, lithology and streams; (b) land-use in 2009 and location of the study sites.

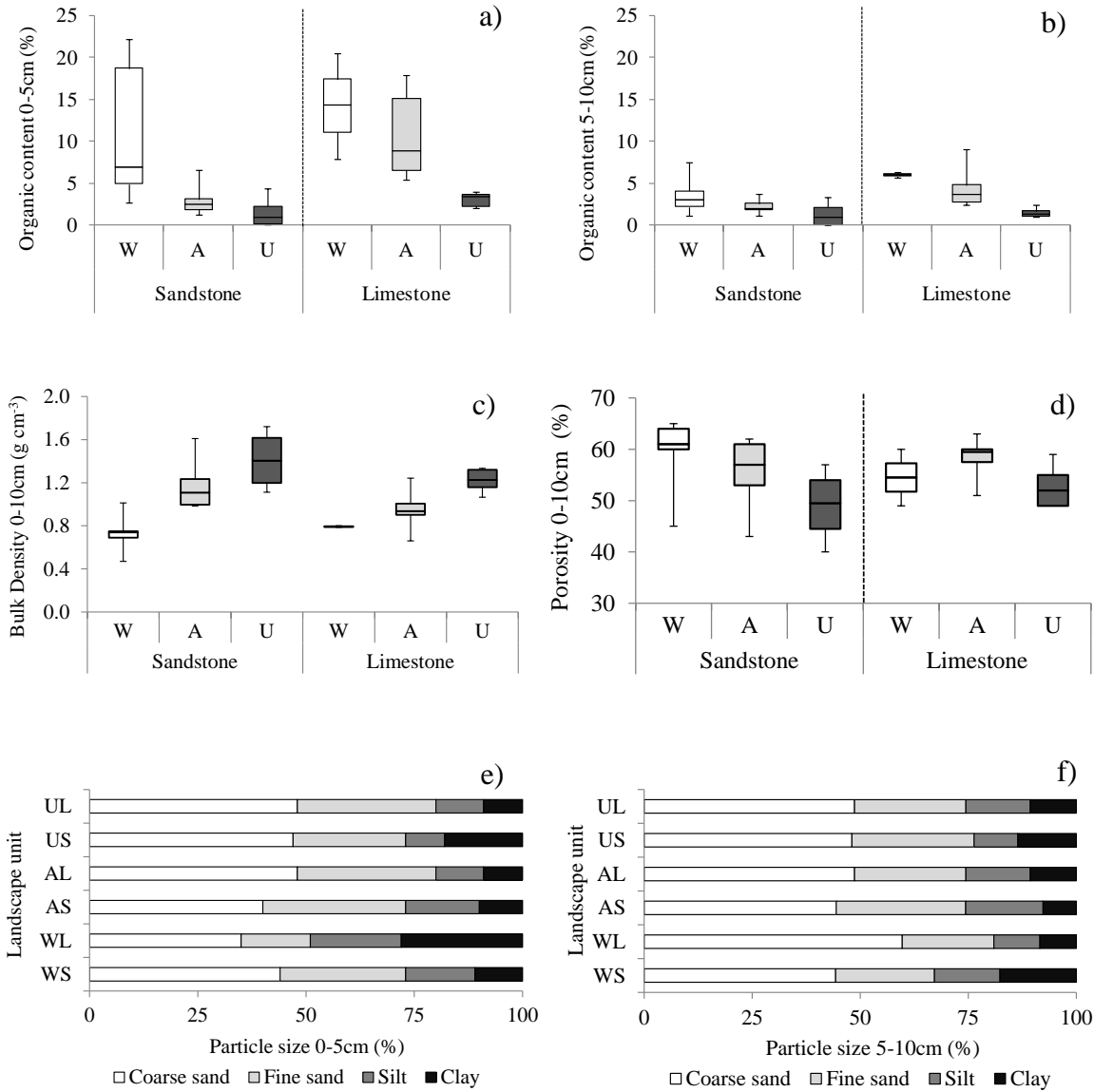


Figure 3 – Soil properties in different landscape units: a) organic matter content at the surface (0-5cm) and b) subsurface (5-10cm), c) bulk density (0-10cm), d) porosity (0-10cm), e) particle size distribution of surface (0-5cm), and f) subsurface soil (5-10cm) (W: woodland, A: agricultural, U: urban, S: sandstone, L: limestone).

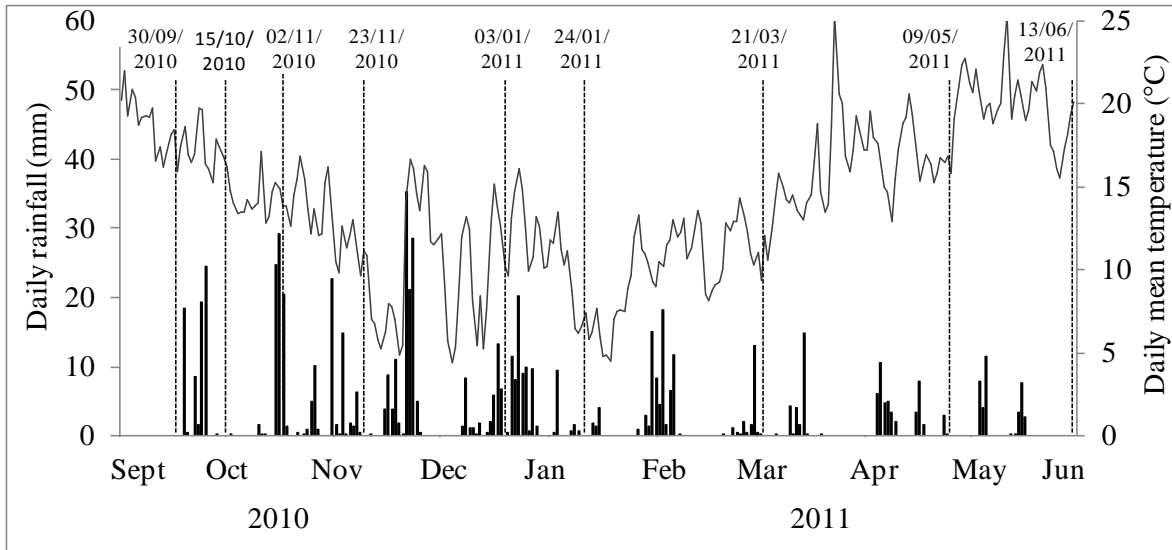


Figure 4 – Daily rainfall and mean daily temperature during the monitoring period September 2010 – May 2011 with dates of field measurements.

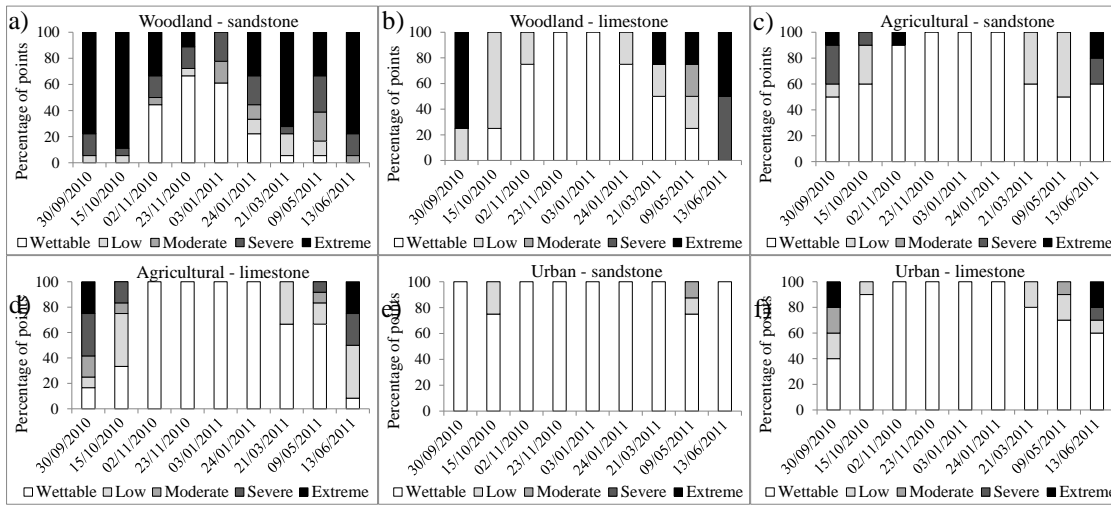


Figure 5 – Temporal variability of surface hydrophobicity for individual landscape units: a) woodland-sandstone, b) woodland-limestone, c) agricultural-sandstone, d) agricultural-limestone, e) urban-sandstone, f) urban-limestone.

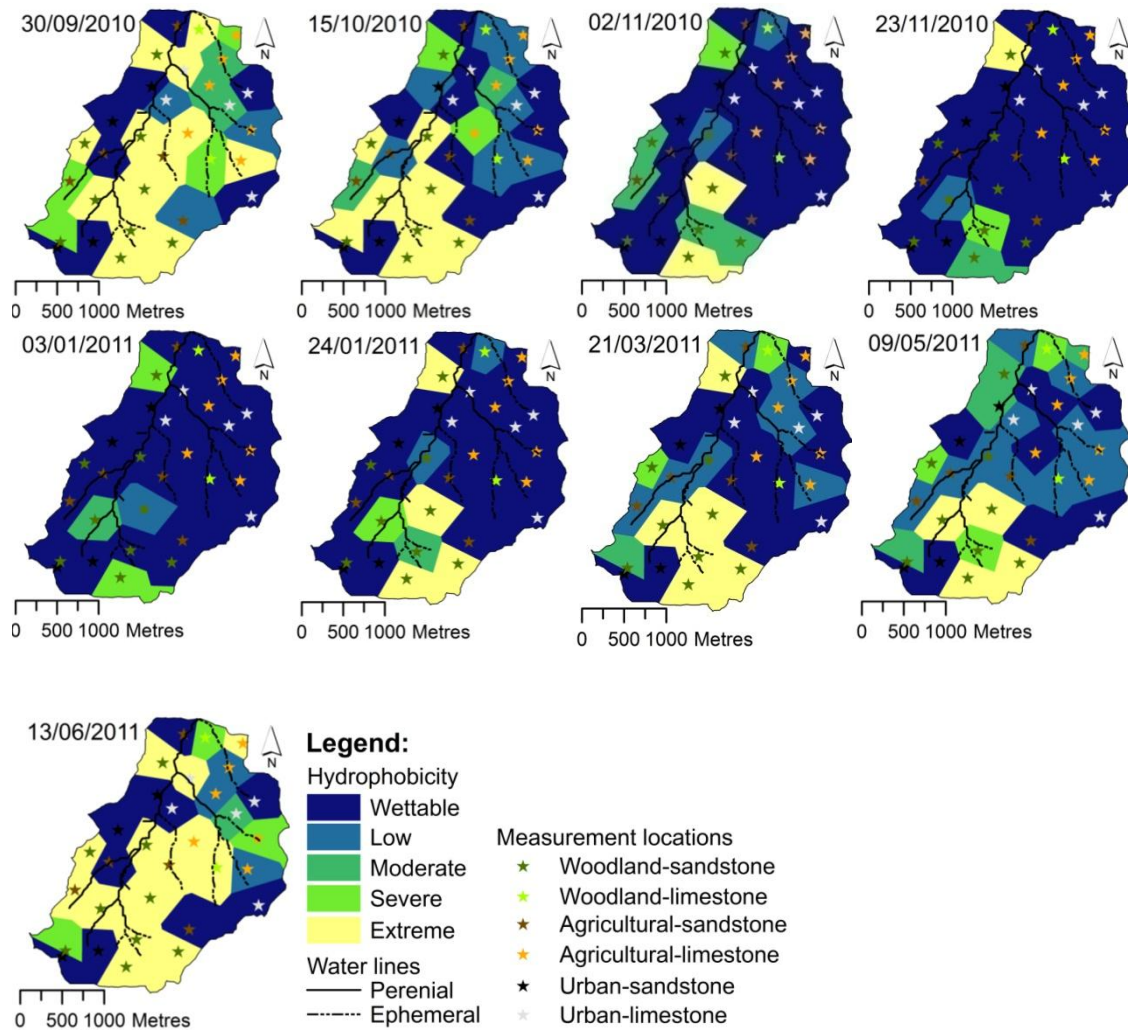


Figure 6 – Spatial variation of median soil hydrophobicity at the measurement dates, based on the Thiessen polygon method.

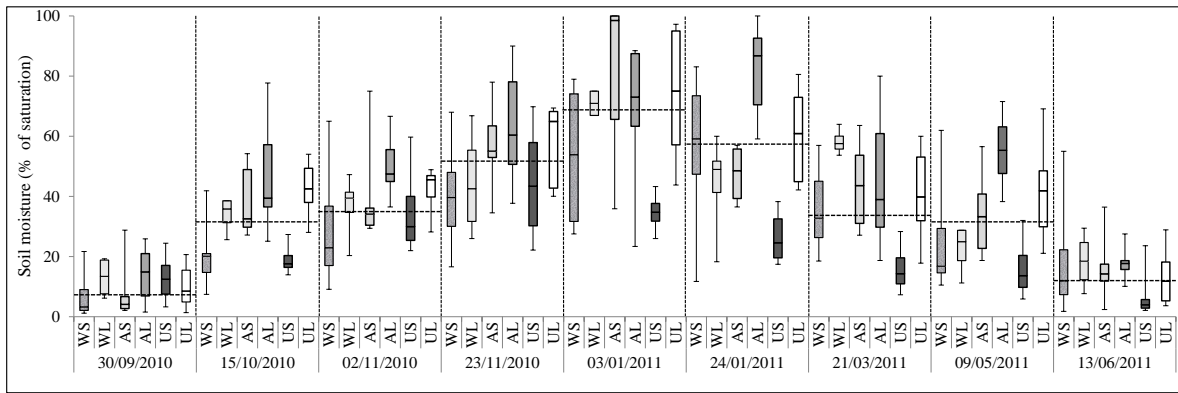


Figure 7 – Box-plots of soil moisture content for the different landscape units for the study period (W: woodland, A: agricultural, U: urban, S: sandstone, L: limestone). Horizontal dashed lines represent median soil moistures across the catchment, for the 9 measurement dates.

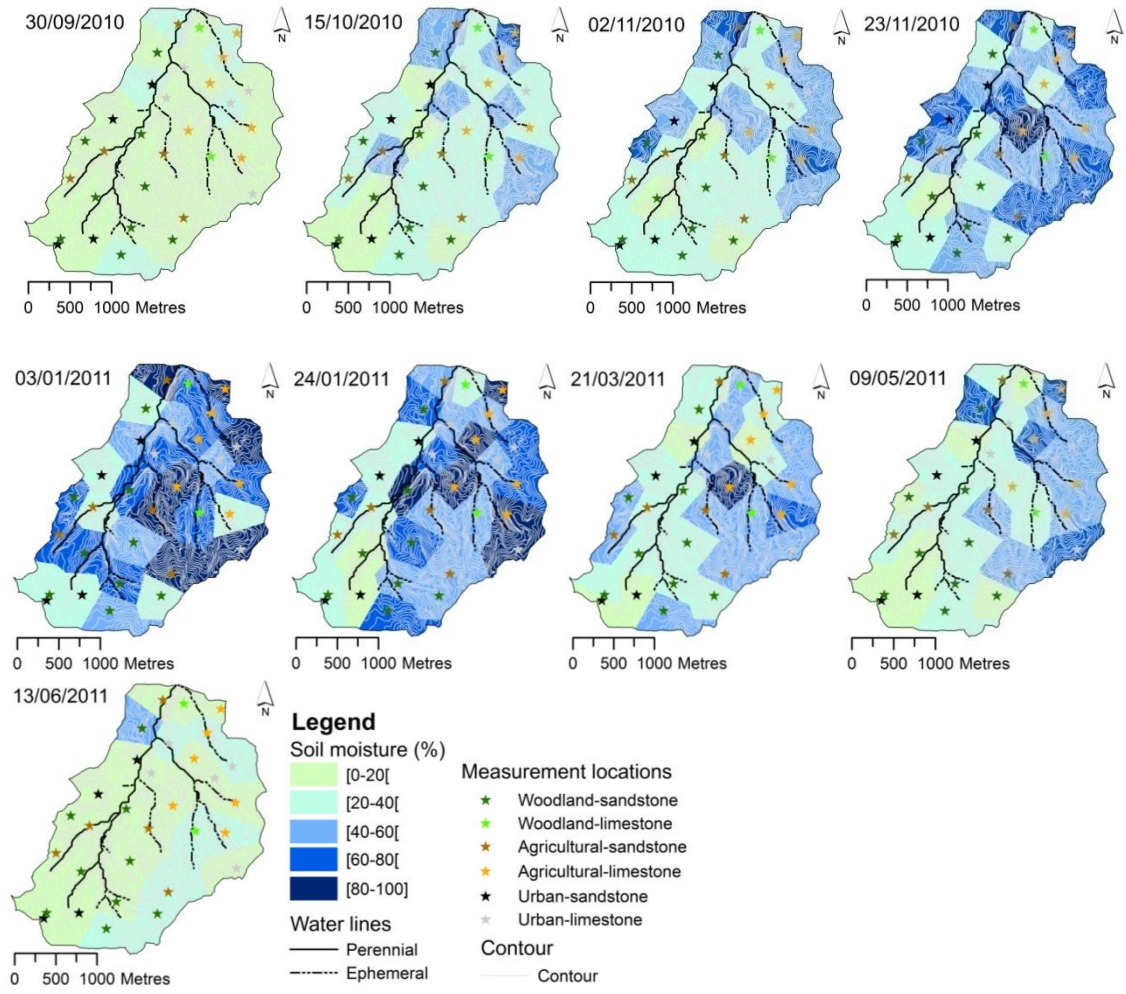


Figure 8 – Spatial distribution in median soil moisture content for each the measurement date, using the Thiessen polygon method.

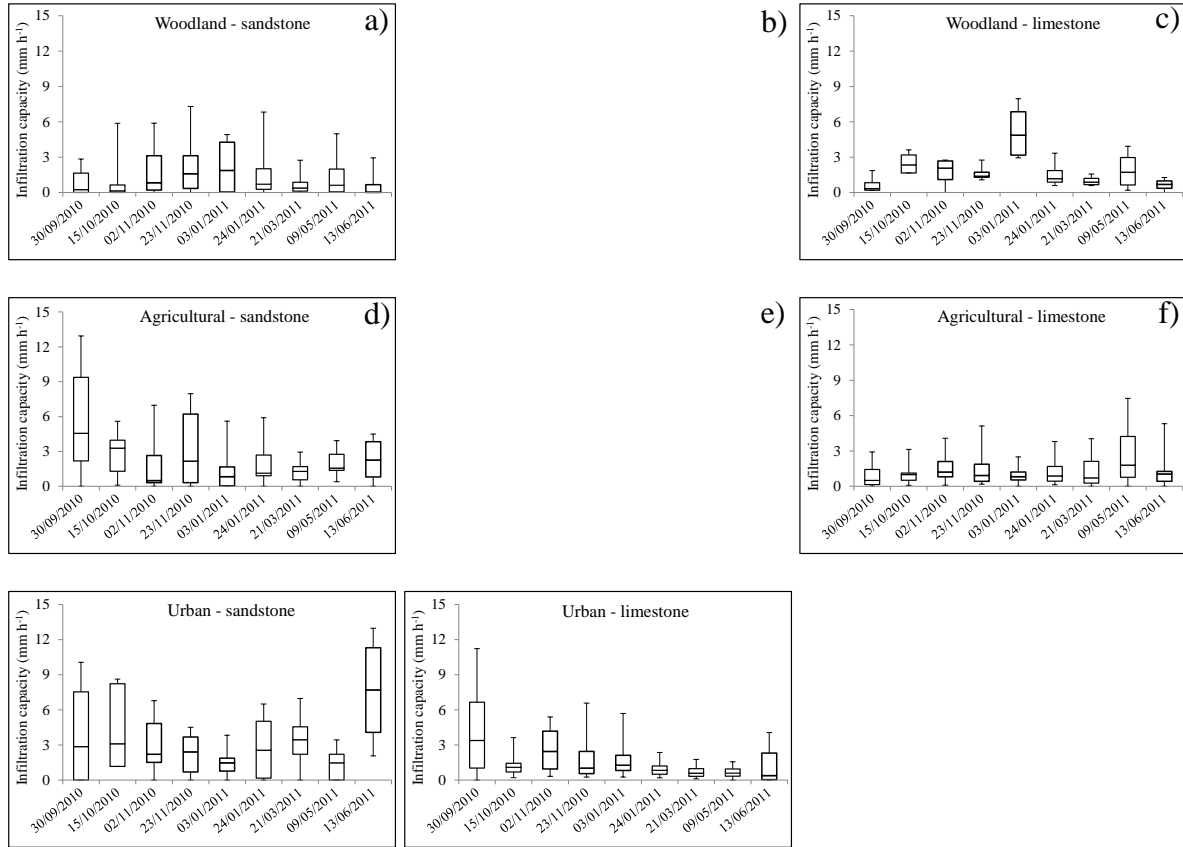


Figure 9 – Box plots of temporal variability of matrix soil infiltration capacity for each landscape unit: a) woodland-sandstone, b) woodland-limestone, c) agricultural-sandstone, d) agricultural-limestone, e) urban-sandstone, f) urban-limestone.

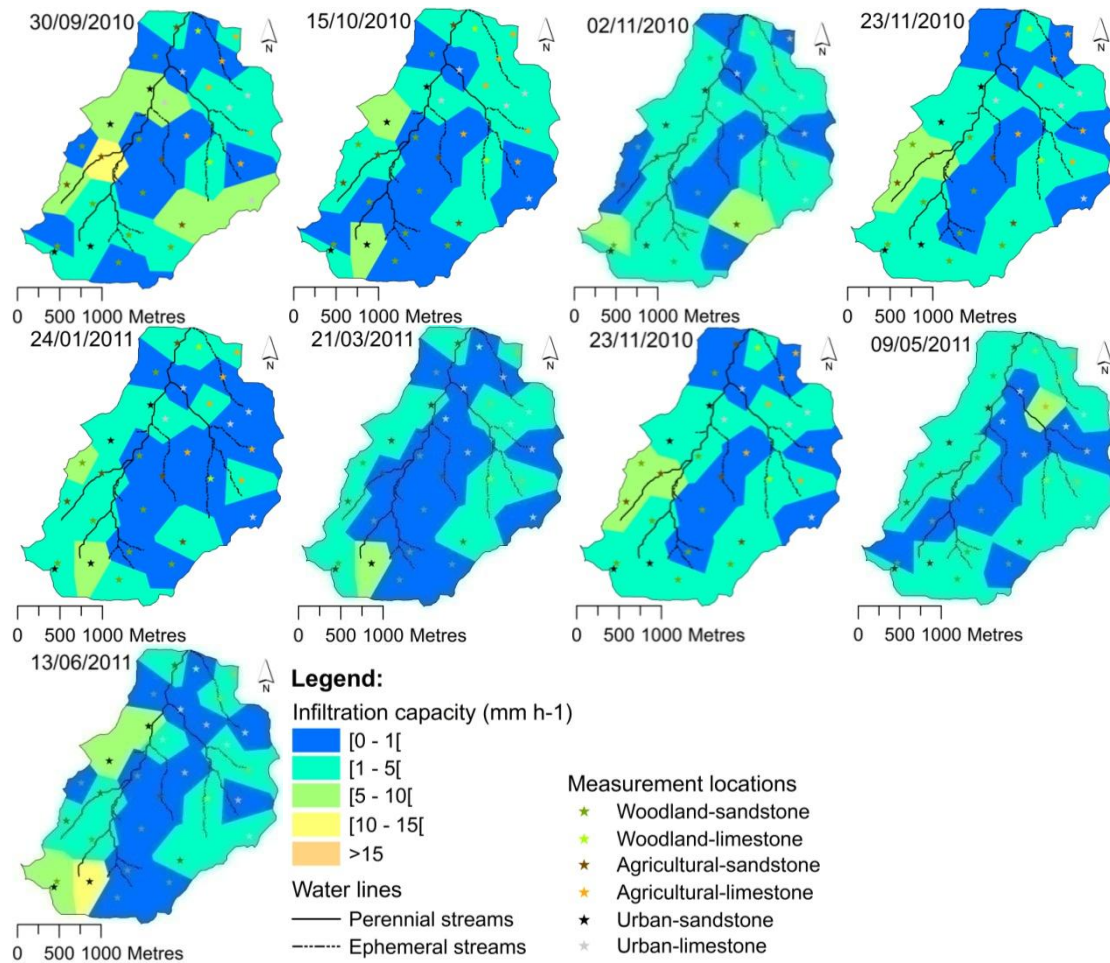


Figure 10 - Spatial variation in median matrix soil infiltration capacity at each measurement date, using the Thiessen Polygon method.

Table 1 – Rainfall and mean temperature in the days prior to measurement dates.

Measurement date	Total rainfall between measurements (mm)	Antecedent rainfall (mm)				Mean temperature during previous 5 days (°C)
		2 days	5 days	10 days	30 days	
30/09/2010	-	0.0	0.0	0.0	5.0	18.9
15/10/2010	72.6	0.0	0.2	53.8	72.6	16.7
02/11/2010	77.2	1.2	75.4	77.2	131.6	14.1
23/11/2010	66.0	0.4	9.6	49.0	141.8	11.4
03/01/2011	161.5	0.5	26	30.2	131.5	12.3
24/01/2011	82.8	0.7	2.6	12.3	112.5	6.9
21/03/2011	97.0	0.2	0.2	15.8	19.8	13.1
09/05/2011	72.3	0.2	3.1	12.5	47.2	16.3
13/06/2011	37.0	0.0	0.0	0.0	37.0	18.1

Table 2 – Principal Component Analysis results considering only hydrophobicity at different depths and soil moisture variables.

Factors	FC 1
Hydrophobicity (0cm)	0.780
Hydrophobicity (2cm)	0.894
Hydrophobicity (5cm)	0.893
Soil moisture (0-5cm)	-0.595
Cumulative variance explained (%)	64.0

Table 3 - Principal Component Analysis results including hydrophobicity, soil moisture and soil properties at different depths.

Factors	FC 1	FC 2	FC 3
Hydrophobicity (0cm)	-0.108	0.772	-0.230
Hydrophobicity (2cm)	-0.297	0.809	-0.214
Hydrophobicity (5cm)	-0.298	0.777	-0.314
Soil moisture (0-5cm)	0.378	-0.342	0.518
Organic matter content (0-5 cm)	0.044	0.622	0.627
Organic matter content (5-10 cm)	0.247	0.580	0.652
Coarse sand (0-5 cm)	-0.831	-0.163	-0.075
Coarse sand (5-10 cm)	-0.907	-0.150	0.169
Silt (0-5 cm)	0.870	0.183	0.006
Silt (5-10 cm)	0.906	0.170	-0.173
Clay (5-10 cm)	0.714	-0.100	-0.454
Cumulative variance explained (%)	36.3	61.9	76.0

1

2 **Spatiotemporal variability of hydrologic soil properties and the implications for**
3 **overland flow and land management in a peri-urban Mediterranean catchment**

4

5 | C. S. S. Ferreira^{a,b}, R. P. D. Walsh^c, T. S. Steenhuis^d, R. A. Shakesby^c, J. P. N. Nunes^a, C.
6 | O. A. Coelho^a, A. J. D. Ferreira^b

7

8 ^a *CESAM, Department of Environment and Planning, University of Aveiro, Aveiro,*
9 *Portugal*

10 ^b *CERNAS, Coimbra Agrarian Technical School, Bencanta, Coimbra, Portugal*

11 ^c *Department of Geography, College of Science, Swansea University, Swansea, United*
12 *Kingdom*

13 ^d *Department of Biological and Environmental Engineering, Cornell University, Ithaca,*
14 *New York, USA*

15

16 **Corresponding author:** Carla Ferreira, email: carla.ssf@gmail.com, Phone.:
17 +351239802940, Fax: +351239802, Address: Escola Superior Agrária de Coimbra,
18 Bencanta, 3045-601 Coimbra, Portugal

19 **Email addresses of co-authors:** r.p.d.walsh@swansea.ac.uk, jpcn@ua.pt,
20 aferreira@esac.pt, r.a.shakesby@swansea.ac.uk, tammo@cornell.edu, coelho@ua.pt

21 ABSTRACT

22 | Planning of semi-urban developments is often hindered by a lack of knowledge on how
23 | changes in land-use affect catchment hydrological response. The temporal and spatial
24 | patterns of overland flow source areas and their connectivity in the landscape, particularly
25 | in a seasonal climate, remain comparatively poorly understood. This study investigates
26 | seasonal variations in factors influencing runoff response to rainfall in a peri-urban
27 | catchment in Portugal characterized by a mosaic of landscape units and a ~~sub~~-humid
28 | Mediterranean climate. Variations in surface soil moisture, hydrophobicity and infiltration
29 | capacity were measured in six different landscape units (defined by land-use on either
30 | sandstone or limestone) ~~in~~during nine monitoring campaigns at key times over a one-year
31 | period.

32 | Spatiotemporal patterns in overland flow mechanisms were found. Infiltration-excess
33 | overland flow was generated in rainfalls during the dry summer season in ~~the~~
34 | ~~forestwoodland~~ on both sandstone and lime-stone and on agricultural soils on limestone,
35 | due probably in large part to soil hydrophobicity~~to soil hydrophobicity~~. In wet periods,
36 | ~~saturation excess~~saturation overland flow occurred on urban and agricultural soils located
37 | in valley bottoms and on shallow soils upslope. Topography, water table rise and soil depth
38 | determined the location and extent of saturated areas. Overland flow generated in upland
39 | upslope source areas potentially can infiltrate in other landscape units down~~slope~~hill where
40 | ~~with~~ infiltration capacity exceeds~~in excess of the~~ rainfall intensity~~ies~~. Hydrophilic urban
41 | and agricultural-sandstone soils were characterized by increased infiltration capacity during
42 | dry periods, while forest soils provided potential sinks for overland flow when hydrophilic
43 | in the winter wet season. Identifying the spatial and temporal variability of overland flow

44 sources and sinks is an important step in understanding and modelling flow connectivity
45 and catchment hydrologic response. Such information is important for land managers in
46 order to improve urban planning to minimize flood risk.

47 **Keywords:** soil moisture, soil hydrophobicity, infiltration capacity, Mediterranean, spatial
48 and temporal variability, landscape units, overland flow, flow connectivity, urban
49 hydrology.

50

51 1. Introduction

52 Land-use changes associated with urbanization strongly affect hydrological processes.
53 Research into the hydrological effects of urbanization has focused on its impact on runoff
54 processes, but conclusions have proved difficult to extrapolate because of the complex
55 interplay of such parameters like climatic setting (Boyd et al., 1993; Costa et al.,
56 2003), geologically-controlled topography (Wilson et al., 2005), soil properties (López-
57 Vicente et al., 2009; Hardie et al., 2011), vegetation and land-use (Mallick et al., 2009),
58 including land-use change history, and the percentage of impervious terrain surface and its
59 spatial arrangement (e.g. Konrad and Booth, 2005). Variation in the combined effect of
60 these factors is arguably the main reason for observed differences in one of the most
61 important factors related to impact of urban land-use change impacts on hydrology.
62 ~~The combined effect of these factors is one of the most important factors related to land-use~~
63 ~~change impacts on hydrology. In addition, s~~Soil moisture, linked to storage capacity, is
64 recognized as a major runoff-controlling factor, particularly in a Mediterranean climate
65 (Cerdà, 1997). Its seasonal variability can mean that greater rainfall intensity is required for

66 | overland flow initiation in summer than in winter (Cammeraat, 2002). When ~~saturation-~~
67 | ~~excesssaturation~~ overland flow mechanisms are involved, the influence of soil moisture is
68 | more varied and not entirely understood, particularly in urbanizing catchments where its
69 | spatial and temporal variability are rarely reported (Easton et al., 2007).

70 | ~~Although~~ ~~There~~ have been many studies of soil hydrophobicity and its impacts on
71 | infiltration and overland flow in a range of seasonal and sub-humid environments (e.g.
72 | Glenn and Finley, 2010; Carrick et al., 2011; Orfánus et al., 2014), ~~but~~-in areas of
73 | Mediterranean climate they have ~~been~~ mainly ~~focussed~~~~on~~~~to~~ on forested terrain
74 | locations (e.g. Doerr et al., 1996, 1998, 2000; Varela et al., 2005; Keizer et al., 2008;
75 | ~~Shakesby, 2011;~~ Neris et al., 2013; Nyman et al., 2014). Furthermore, ~~r~~Relatively little,
76 | ~~however,~~ is known about ‘switching’ between hydrophobic and hydrophilic conditions in
77 | dry and wet periods respectively and the net effects on catchment hydrological response in
78 | areas affected seasonally by soil hydrophobicity (Leighton-Boyce et al., 2002~~2005~~). In
79 | hydrological modelling of urbanizing areas, the phenomenon has not even been considered.

80 | The seasonal and spatial variability of soil moisture and hydrophobicity on heterogeneous
81 | landscapes affects overland flow sources and sinks, and is critical in understanding flow
82 | transfer between different landscape units (Kirkby et al., 2002; Bull et al., 2003). Relatively
83 | little research into such hydrological effects has been carried out in Mediterranean
84 | environments, so the impact of marked seasonal changes on runoff processes is not well
85 | understood. This is even truer of peri-urban areas, which represent the transition zone
86 | between urban and rural environments on the outskirts of cities and which often comprise
87 | a mosaic of land-use types. Here, better understanding of the interplay between ~~of~~ these

88 factors would help ~~in the prediction of to predict~~ the flow response and ~~estimation of~~
89 ~~estimate~~ the overland flow amount reaching any point in a catchment (Borselli et al., 2008).

90 This paper focuses on temporal and spatial variations in key soil hydrological properties
91 (soil moisture, hydrophobicity and infiltration capacity) in different land-uses in a small,
92 peri-urban, ~~partly~~ limestone, ~~partly~~ sandstone catchment in central Portugal. The catchment
93 has changed rapidly from agricultural land and forestry to a discontinuous urban fabric,
94 with urban patches interrupting both woodland and semi-abandoned agricultural terrain.
95 The urban areas comprise a complex mosaic of tarmac, gardens and walls, in addition to
96 buildings and derelict ground. The distinctive mosaic pattern of the catchment is typical of
97 Portuguese urbanization. Specific aims of the paper are to: 1) assess spatial and temporal
98 variability of hydrological soil properties in different land-uses/lithology landscape units in
99 the catchment; 2) identify seasonal changes in overland flow sources; 3) evaluate the
100 impact of landscape units (characterized by different land-uses and lithologies) on flow
101 connectivity and streamflow response; and 4) explore implications of urbanizing mosaics
102 for landscape management and urban planning, especially with respect to streamflow
103 regimes and flood risk.

104

105 2. Study area

106 The study site is the S-N elongated *Ribeira dos Covões* catchment (40°13'N, 8°27'W; 6.2
107 km²) in the suburbs of Coimbra, the largest city of central Portugal. The climate ~~(as~~
108 ~~recorded at Bencanta, 0.5 km north of the catchment boundary)~~ is humid Mediterranean,
109 with a mean annual temperature of 15°C, a mean annual rainfall of 892 mm (INMG, 1941-
110 2000), hot and dry summers (~~only~~ 8% of rainfall in the months June-August) and wet

111 winters (Figure 1). The main watercourse is perennial, supplied by several springs, and
112 there are several smaller ephemeral tributaries (Figure 2). The geology (Figure 2a)
113 | comprises Jurassic dolomitic and marly limestone in the east (49% of the catchment area),
114 | and Cretaceous and Tertiary sandstones, conglomerates and mudstones in the west (47% of
115 | the area), with some Pliocene-Quaternary sandy-conglomerate ([sedimentcolluvium](#)) and
116 | alluvial deposits (4% of the area) in the main valleys. Soils are generally deep (>3m)
117 Cambisols and Podzols (Tavares et al., 2012). Only on steeper slopes in the northwest is
118 | soil depth [less than](#)<40 cm. Altitude ranges from 29m to 201m. The average slope is 9°, but
119 | [with](#)-a few slopes reaching up to 46°.

120 The catchment, totally rural until 1972, underwent discontinuous urbanization in 1973 -
121 1993, followed by urban consolidation after 1993 (Tavares et al., 2012). The agricultural
122 area, mainly olives and arable land, declined from 48% in 1958 to 4% of the catchment in
123 | 2009. Woodland increased from [46%](#) to 66% over the same period, changing also in nature
124 | from *Quercus suber* and mixed woodland to large commercial plantations of pine (*Pinus*
125 | *pinaster*) and [eucalyptseucalypt](#) (*EucalyptusEucalypt globulus*) (Tavares et al., 2012).
126 | Urban land-use increased from 6% in 1958 to 30% in 2009 (Figure 2b), [of which 14%](#)
127 | [comprised impervious surfaces and 16% urban soil. The result was a mosaic of resulting in](#)
128 | older urban cores, with detached houses and gardens, and newer apartment blocks. There
129 | are also a few small industrial premises, recreational areas and an enterprise park begun in
130 2009. Urban storm runoff (from roofs, streets and concrete paved areas) is either piped to
131 tributaries or flows directly towards the stream network. Where urban buildings and derelict
132 urban land are surrounded by fields, however, stormwater is not controlled.

133

134 3. Methodology

135 3.1 Research design

136 A network of 31 representative sites was established in the catchment to assess
137 hydrological properties of the six different land-use/lithology combinations or “landscape
138 units” (Figure 2b). There were: 1) 11 sites in woodland, 9 being on sandstone (dominated
139 by ~~eucalypt~~eucalypt, pine and mixed deciduous forest), and 2 on limestone (in small
140 areas of oak and mixed deciduous woodland); 2) 11 sites on agricultural fields, including 5
141 on sandstone (dominated by light grazing pasture, small olive groves and minor cultivated
142 patches) and 6 on limestone (in olive groves and abandoned fields undergoing natural
143 succession); and 3) 9 sites on uncultivated urban soil, 4 on sandstone (~~mainly~~-bare soil sites
144 associated with construction and open spaces with ground vegetation between houses) and
145 5 on limestone (~~mainly~~-derelict spaces between houses and between houses and roads).

146 At each site, soil moisture content, hydrophobicity and soil matrix infiltration capacity were
147 monitored 9 times between September 2010 and June 2011, to cover a representative range
148 of antecedent weather and seasonal conditions, including prolonged periods of wet weather
149 and long dry spells. Temperature and rainfall data during the study period were provided by
150 the national meteorological weather station 12G/02UG, located at Bencanta, 0.5 ~~K~~km
151 Nnorth of the study catchment.

152 Replicate measurements of soil hydrological properties, spaced approximately 1m apart,
153 were ~~carried out~~performed at each site. In total, 558 measurements of each parameter were
154 obtained.

155 Three soil samples (c. 100g each) were collected on the nine occasions at each site to assess
156 surface soil moisture (0-5cm depth). Additional soil samples were taken at all sites on 23rd
157 November 2010 to determine dry bulk density, rock fragment content, organic matter and
158 particle size distribution. The excavation method (15×15cm and 10cm depth) was used for
159 bulk density and rock fragment analyses (three samples per location) (Dane and Topp,
160 2002). Composite samples were also collected at depths of 0-5cm and 5-10cm for organic
161 matter and particle size distribution analyses. Each composite sample comprised 17 sub-
162 samples collected at 15cm intervals along a 2.4m transect at each site.

163

164 **3.2 Field methods and procedure**

165 Soil matrix infiltration capacity was measured using a Minidisk Tension Infiltrometer
166 (Decagon Devices; 4.5cm diameter and pressure head of -3.0cm). Before measurements,
167 ground vegetation was trimmed and surface litter carefully removed. Following preliminary
168 trials, measurements were taken over 30 minutes by which time steady-state conditions
169 were assumed to have been reached. Unsaturated hydraulic conductivity was calculated
170 using published guidelines (Zhang, 1997; Li et al., 2005; Decagon, 2007). Infiltration
171 capacity, however, was calculated from the final 10 minutes of data (i.e. when the values
172 were judged to have stabilized). Taking all measurements as recommended by Decagon
173 (2007) would have given spurious values due both to initially high infiltration in
174 hydrophilic soils and to delayed infiltration when soils were hydrophobic.

175 Near each infiltrometer location, soil hydrophobicity was assessed at depths of 0, 2 and
176 5cm using the Molarity of an Ethanol Droplet (MED) technique (Letey, 1969; Doerr et al.,

177 | 1998). Fifteen drops of [pure-distilled](#) water and then progressively higher concentrations of
178 | ethanol were applied until the lowest concentration was identified at which at least 8 out of
179 | 15 drops were absorbed within 5 seconds. Ethanol concentrations of 0, 3, 5, 8.5, 13, 18, 24
180 | and 36 percent by volume were used. The soil was considered wettable ([hydrophilic](#)) when
181 | [pure-distilled](#) water drops infiltrated within 5 seconds. [The; hydrophobicity](#) classes [of levels](#)
182 | [of hydrophobicity](#) used were: low for 3 and 5% ethanol, moderate for 8.5 and 13%, severe
183 | for 18 and 24%, and extreme for 36% (Doerr [et al.](#), 1998).

184

185 | **3.3 Laboratory methods**

186 | Soil physical properties (bulk density, rock [fragmenteontent](#), organic matter content and
187 | particle size) were analysed using standard methods (Dane and Topp, 2002). Bulk density
188 | was obtained from undisturbed samples dried at 105°C. Disturbed soil samples were oven-
189 | dried at 38 °C until a constant weight was reached, and the <2mm fraction extracted. The
190 | >2mm rock fragment content was calculated as a percentage of the total dry soil sample
191 | weight. The organic matter content was analyzed by oxidation at 600°C and detected by
192 | close infra-red, using SC-144DR equipment (Strohlein Instruments). Porosity was
193 | calculated from the dry bulk density and the organic matter content according to methods
194 | recommended by Dane and Topp (2002), assuming a [soil mineral](#) [soil-particlebulk](#) density
195 | of 2.65 g cm⁻³ and organic matter bulk density of 0.90 g cm⁻³. The particle size distribution
196 | of the minerogenic component of the soil samples was determined where organic matter
197 | content was > 2% either [by](#): 1) [by](#)-oxidation using hydrogen peroxide (6%), for samples
198 | with organic matter contents of -2-4%; or 2) heating to 550°C for samples with higher

199 values. The samples were then dispersed using Na-hexametaphosphate and the ultrasonic
200 method (Dane and Topp, 2002). Particle size distribution was subsequently determined
201 using a combination of sieving, gravity sedimentation and pipette analysis. Soil texture
202 classes were based on the ISSS international classification [\(Soil Survey Division Staff,
203 1993\)](#).

204 Soil moisture content was assessed on each measurement occasion by the
205 thermogravimetric method following oven-drying at 105°C. Soil saturation was than
206 estimated by dividing the volumetric water content (estimated from gravimetric water
207 content and bulk density) by porosity.

208

209 **3.4 Data analysis**

210 The statistical significance of soil property differences between the land-use/lithology
211 landscape units was investigated first using the non-parametric Kruskal–Wallis H test
212 (SPSS 17.0). Where significant differences between units were identified, the Least
213 Significant Difference (LSD) Post-Hoc test was applied to identify distinct units or groups
214 of units. The same tests and procedure were applied to differences in soil hydrological
215 properties between measuring dates. A 95% level of significance ($p < 0.05$) was used. In
216 addition, Pearson-r correlation coefficients were calculated to assess linear relationships
217 between: 1) soil properties (organic matter content, bulk density and particle size) and soil
218 moisture, soil hydrophobicity and infiltration capacity ($n=64$); and 2) antecedent weather
219 and soil hydrological properties on each monitoring occasion. Principal Component

220 Analysis was used to quantify the infiltration variance explained by the correlated variables.
221 Although the data were not normally distributed, it was considered useful to apply this
222 technique for explorative purposes to improve understanding of the controls on overland
223 flow. Spatial patterns of hydrological soil properties were analyzed using geostatistical
224 methods, based on Thiessen Polygons, carried out using ArcGIS 9.3 software.

225

226 **4. Results and analysis**

227 **4.1 Soil properties**

228 Soil organic matter was generally higher and more consistent for surface (0-5cm) than
229 subsurface soil (5-10cm) (Figures 3a and 3b). For both soil depths, organic matter content
230 increased from urban (1-3%) to agricultural (3-9%) and woodland soils (averaging 7% and
231 14% on sandstone and limestone, respectively). In the woodland and agricultural-limestone
232 landscape units, organic matter was highly variable, but greater than in agricultural-
233 sandstone and urban soils ($p < 0.05$).

234 Bulk density increased from woodland (0.7 g cm^{-3}) to agricultural (1.0 g cm^{-3}) and to urban
235 soils (1.2 g cm^{-3}) (Figure 3c). In woodland and urban soils, bulk density was similar on
236 both lithologies ($p > 0.05$), but it was higher for agricultural-sandstone than agricultural-
237 limestone soils (median values of 1.1 g cm^{-3} and 0.9 g cm^{-3}) ($p < 0.05$). Values for the latter
238 were similar to woodland, whereas agricultural-sandstone values were similar to urban soils
239 ($p > 0.05$). Bulk density decreased with as soil organic matter increased ($r = -0.341$,
240 $p < 0.001$).

241 | Soil porosity ranged ~~from~~between 40 ~~and~~to 65% (Figure 3d) with generally lower values
242 | for urban soils, despite no significant difference ($p>0.05$). Greater heterogeneity was found
243 | ~~for~~in agricultural soils, with higher values on limestone than sandstone ($p<0.05$). Rock
244 | fragment content ranged from 14 to 57% and was similar amongst landscape units
245 | ($p>0.05$). Particle size varied between individual sites (Figure 3e and 3f), but not between
246 | landscape unit averages ($p>0.05$), with sandy-loam and loamy-sand textures dominating.
247 | Particle size distribution affected bulk density, which increased with larger coarse sand
248 | ($r=0.189$, $p<0.001$) and clay fractions ($r=0.115$, $p<0.001$), and diminished with larger fine
249 | sand ($r=-0.287$, $p<0.001$) and silt fractions ($r=-0.190$, $p<0.001$).

250

251 | **4.2 Antecedent weather conditions**

252 | ~~Overall~~ Rainfall and temperature patterns during the monitoring period are shown in
253 | Figure 4 and antecedent conditions for each measurement date are summarized in Table 1.
254 | Antecedent 30-day rainfall ranged from 5.0mm (30/09/2010) to 141.8mm (23/11/2010).
255 | Antecedent 5-day rainfall ranged from rainless (prior to 30/09/2010 and 13/06/2011) or
256 | trace (0.2mm prior to 15/10/2010 and 24/01/2011) to 26.0mm (prior to 03/01/2011) and
257 | 75.4mm (prior to 02/11/2010).

258

259 | **4.3 Soil hydrophobicity**

260 | Soil hydrophobicity varied greatly in severity and ~~%~~ frequency both between landscape
261 | units and with season and antecedent weather (Figures 5 and 6). Surface (0cm) and
262 | subsurface (2cm and 5cm) soil (results not shown) exhibited similar spatial and temporal

263 trends. Hydrophobicity increased with temperature ($r=0.337$, $p<0.001$) and decreased with
264 antecedent 2- and 30-day rainfall ($r=-0.298$ and -0.373 respectively, $p<0.001$). The area
265 affected by hydrophobicity was larger in summer (50% of all measurement sites) and
266 ~~hydrophobicity was~~ more severe in summer than in winter. ~~It~~ disappeared in late
267 November and January, except at woodland-sandstone sites (<20% of all sites).

268 Hydrophobicity was of greater severity and spatial extent in covered larger areas of
269 woodland, where after dry spells it required several rainfall events to lessen its impact,
270 particularly on sandstone (Figures 5a and 5b). At agricultural sites especially on limestone
271 (Figures 5c and 5d), hydrophobicity was also present in dry periods but was less severe
272 than on woodland and rapidly decreased in percentage% frequency following rainstorms
273 and ~~disappeared~~~~vanished~~ in wetter periods. Urban soil was mostly hydrophilic/wettable
274 (Figures 5e and 5f), with hydrophobicity only affecting a minority of sites even in the driest
275 periods. Re-establishment of hydrophobic conditions in dry weather also varied with land-
276 use, being rapid in woodland, particularly on sandstone where it re-appeared by 24 January
277 2011, but far slower on agricultural and urban soils, where it was absent until March 2011.
278 Significant differences between woodland and urban soils were found ($p<0.05$).

279 A positive correlation was identified between hydrophobicity severity and organic matter
280 content ($r=0.308$ for surface and 0.345 for subsurface soil, $p<0.001$). Hydrophobicity was
281 correlated with particle size, increasing with surface fine sand ($r=0.197$, $p<0.001$) and
282 decreasing with subsurface clay fraction ($r=-0.226$, $p<0.001$). ~~This was,~~ reflected also in a
283 negative correlation with bulk density ($r=-0.240$, $p<0.001$). Hydrophobicity was also found
284 to be inversely correlated-increased with ~~decreased~~ soil moisture ($r=-0.363$, $p<0.001$,
285 $n=558$). Nevertheless, hydrophilic/wettable conditions were recorded at least at some

286 | ~~locations~~ in all ~~agricultural and urban~~ landscape units ~~over the range at all of~~ soil moisture
287 | contents recorded, ~~whereas except~~ in woodland ~~where~~ soil was invariably hydrophobic at
288 | contents below 20%. There seemed to be no particular moisture threshold, although at 75%
289 | of the measurement sites, at least low hydrophobicity was characteristic below 45% soil
290 | moisture. Hydrophobicity, however, was recorded at a few woodland sites with 70% soil
291 | moisture.

292

293 4.4 Soil moisture

294 | Surface soil moisture varied with antecedent weather (Figures 7 and 8), increasing after
295 | rainfall (although correlations were weak: $r=0.375$, 0.168 , 0.258 and 0.541 with ~~-2~~, 5-, 10-
296 | and ~~30~~-day antecedent rainfall, respectively, $p<0.001$); and declining with higher
297 | temperature ($r=-0.593$ with values in previous 5 days, $p<0.001$). During summer and after
298 | long rain-free periods (30/09/~~30+0-2010~~ and 13/06/2011), soil became dry (<20% moisture)
299 | across the catchment.

300 | Land-uses responded differently to rainfall; and limestone areas generally had higher soil
301 | moisture than sandstone ~~areas~~. This was very pronounced on 2nd November 2010 (Figure
302 | 7). Soil moisture was generally lower in urban sandstone soils throughout the year, but also
303 | on woodland ~~sandstone~~ -in winter ~~and in~~; ~~dry-wet and as well as wet-dry transition and in~~
304 | ~~dry to wet transition~~ periods ~~and vice versa~~. Indeed, the lowest post--summer (30/09/2010)
305 | median ~~soil~~ moisture content was ~~recorded~~ in woodland ~~-sandstone~~ areas, where it persisted
306 | until late autumn (23/11/2010). Conversely, agricultural and urban limestone soils generally
307 | exhibited higher moisture contents, especially in the wettest periods, when soil saturation
308 | occurred at a few valley-floor ~~agricultural and urban soil~~ sites near streams (Figure 8).

309 Nevertheless, the locations and sizes of wettest areas in *Ribeira dos Covões* changed
310 through time, and ~~few~~ high soil moisture values were recorded occasionally at a minority of
311 woodland sandstone sites in winter. In general, soil moisture content increased with higher
312 greater silt ($r=0.220$, $p<0.001$) and clay ($r=0.163$, $p<0.001$) fractions.

313

314 **4.5 Infiltration capacity**

315 Soil matrix infiltration capacity in the *Ribeira dos Covões* catchment was generally low,
316 despite occasional higher values (Figures 9 and 10). In general, sandstone soils recorded
317 greater permeability than limestone soils. Land-use also affected infiltration capacity but
318 differences varied with season and weather (Figure 9). Generally, woodland recorded
319 higher values in wet than dry periods ($p<0.05$), with median values increasing from 0.1 -
320 0.2 mm h^{-1} on 13/06/2011 and 30/09/2010 to 2.8 mm h^{-1} on 03/01/2010. Nevertheless, after
321 the summer, higher infiltration capacity in woodland occurred earlier on limestone than
322 sandstone. Urban soils showed the opposite trend ($p<0.05$), with median infiltration
323 capacity diminishing from 2.6 mm h^{-1} on 13/06/2011 and 3.1 mm h^{-1} on 30/09/2010 to 1.4
324 mm h^{-1} on 03/01/2010, ~~withand showing~~ slightly higher values on sandstone than on
325 limestone. In agricultural areas, the fall in median infiltration capacity (from 2.5 mm h^{-1} on
326 30/09/2010 to 0.8 mm h^{-1} on 03/01/2010) was ~~not~~ n-statistically significant.

327 Infiltration capacity increased with sand content ($r=0.228$ and $r=0.201$ for surface and
328 subsurface soil respectively, $p<0.001$), but decreased with clay fraction ($r=-0.140$ for
329 subsurface soil, $p<0.001$) and organic matter ($r=-0.149$, $p<0.001$). Statistically significant
330 correlations were also found between infiltration capacity and hydrophobicity ($r=-0.314$

331 and -0.111 at 0cm and 2cm depth respectively, $p < 0.001$), as well as soil moisture ($r = -0.117$,
332 $p < 0.001$).

333 Generally, infiltration capacity was significantly correlated with hydrophobicity and soil
334 moisture, but the lower correlation coefficients may be because infiltration capacity was
335 only calculated during the last 10 minutes, and hydrophobicity and soil moisture were
336 measured separately on adjacent soil. Nevertheless, Principal Component Analysis (PCA)
337 showed that despite the complex interaction between hydrophobicity and soil moisture,
338 these variables together explain 63% of total infiltration capacity variance (Table 2). When
339 particle size characteristics (surface and subsurface coarse sand and silt fractions, and
340 subsurface clay) and organic matter content (surface and subsurface) are considered, the
341 three component variables together explain 76% of infiltration variance (Table 3).
342 However, the results of PCA must be interpreted as only indicative, since the variables do
343 not follow the normal distribution that is strictly required by the approach.

344

345 5. Discussion

346 5.1 Characteristics of the landscape units and their influence on overland flow

347

348 **Interpretation of soil properties**

349

350 **5.1.1 ~~Organic matter, bulk density and particle size~~ Woodland landscape units**

351

352 Woodland environments showed the highest soil organic matter content over the catchment.

353 The high variability of this soil property within woodland areas may be due to differences

354 in tree species and management practices, affecting the litter layer thickness. ~~The lower~~

355 organic matter of ~~Eucalypt-dominated~~ than other woodlands ~~areas tended to have~~

356 ~~relatively low organic matter, possibly may reflecting~~ (a) periodic understorey clearance to

357 ~~help prevent wildfires and (b), but also~~ low understorey vegetation caused by reduced water
358 ~~availability (DeBano, 2000). The denser root system associated with larger vegetation cover~~
359 ~~may favoured low values of soil bulk density. The generally low values of soil bulk density~~
360 ~~in woodland units may be the outcome of higher organic matter in woodland soils than in~~
361 ~~soils of the other landscape units~~~~woodland units may the outcome of the higher organic~~
362 ~~matter than of other landscape units~~ and the denser root systems associated with a tree
363 ~~cover. Reduced bulk density is also characteristic of~~~~was reported in~~ soils with greater
364 ~~organic matter, since it helps the formation of soil aggregates and structure (Celik et al.,~~
365 ~~2010).~~

366 ~~Denser vegetation cover, however, provided~~ The greatest soil hydrophobicity of woodland
367 ~~units can be linked to the species involved and their organic matter produced. Despite all~~
368 ~~the land uses revealed greater~~Seasonal changes in hydrophobicity, with high values in
369 ~~summer and considerable disappearance in winter, this seasonal variability was more~~
370 ~~pronounced~~~~evident~~ in woodland ~~areas~~ than other landscape units and is in accordance ~~This~~
371 ~~seasonal pattern of hydrophobicity accords~~ with previous studies (e.g., Dekker and
372 ~~Ritsema, 1994; Doerr et al., 2000; Martínez-Zavala and Jordán-López, 2009). Nonetheless,~~
373 ~~Within woodland, however, hydrophobicity was more extensive, and severe and~~
374 ~~persistent in sites over~~laying sandstone than limestone (Figures 5a and 5b). Thus in
375 ~~woodland-sandstone areas~~ areas a larger number of rainfall events were required for the
376 ~~soil to become hydrophilic, and even during the wettest periods, hydrophobicity persisted in~~
377 ~~a few soil sites. This is probably because~~Vegetation density and type is apparently
378 ~~important in accounting for differences in spatiotemporal patterns of hydrophobicity, since~~
379 ~~sandstone areas were mainly dominated by eucalypt and pine plantations, whereas on~~
380 ~~limestone, oak is more dominant and pine were more representative. In the woodland~~

381 ~~sandstone areas, larger number of rainfall events were also required for the soil became~~
382 ~~hydrophilic, and even during the wettest settings, hydrophobicity persisted in few soil~~
383 ~~spots. Hydrophobicity is caused, notably, by the hydrophobic substances released by~~
384 ~~vegetation. The type of resins, waxes and aromatic oils of produced by eucalypt (Doerr et~~
385 ~~al., 1998; Jordán et al., 2008) woodland is thought to have caused hydrophobicity to be~~
386 ~~more extensive and resistant than in the other woodland stands, with hydrophobicity :~~
387 ~~Previous studies reported hydrophobicity, particularly in eucalypt stands, was able to~~
388 ~~persist following rainfall of as much as 200mm in 2 months (Ferreira, 1996; Doerr and~~
389 ~~Thomas, 2000). In contrast, in woodland-limestone areas, hydrophobicity was less severe~~
390 ~~and easier to switch to hydrophilic conditions because oak, which is not usually associated~~
391 ~~with hydrophobic soil (Zavala et al., 2009), is the dominant vegetation.~~

392 Generally, woodland areas were also characterized by a quicker re-establishment of
393 hydrophobic conditions after rainfall events, comparing with the other landscape units,
394 particularly under eucalypt plantations. The rate of re-establishment would depend on the
395 biological productivity of the ecosystem (Doerr and Thomas, 2000; Hardie et al., 2012), the
396 type of hydrocarbon substances produced and microbial activity (Keizer et al., 2008).
397 Santos et al. (in press) report greater dynamism, and more frequent hydrophobic conditions
398 in eucalypt than in pine.

399 ~~Results from Ribeira dos Covões showed a positive correlation between hydrophobicity~~
400 ~~severity and organic matter content, which may also explain the greater hydrophobicity~~
401 ~~within woodland areas. This tallies with findings elsewhere (e.g. Dekker and Ritsema,~~
402 ~~2000), but organic matter type and quality are more important than amount as demonstrated~~
403 ~~by the differences between woodland species.~~

404 Nevertheless, differences in hydrophobicity ~~particle size~~ between sandstone and limestone,
405 may also be linked ~~to~~with differences in ~~particle size, hydrophobic conditions, considering~~
406 ~~given the statistically significant (albeit weak) positive correlation found between~~
407 ~~hydrophobicity and sand-fraction. This correlation has~~ ~~was~~ also been recorded ~~observed~~
408 ~~elsewhere by other authors~~ (e.g. DeBano, 1991; McKissock et al., 2000), although a few
409 studies ~~and~~have reported hydrophobicity ~~in~~under finer-textured soils (e.g. Doerr and
410 Thomas, 2000).

411 The higher evapotranspiration associated with a forest ~~Greater vegetation cover~~ (e.g.
412 Holden, 2008) ~~and particularly trees, are accomplished with high evapotranspiration, may~~
413 ~~explaining the lowest soil moisture contents recorded~~ ~~observed~~ during dry periods ~~in~~
414 ~~woodland, compared~~ing with in the other land-uses (Figure 7); ~~Greater interception~~
415 ~~provided by woodland would be particular importance, in percentage terms, in small~~
416 ~~rainfall events (Holden, 2008). Between transition periods of dry to wet settings and vice~~
417 ~~versa, though shading by~~and ground vegetation and litter ~~eovers~~ can ~~reduces~~ soil moisture
418 loss in warm, sunny conditions. ~~The~~ ~~More intense~~over, hydrophobic conditions ~~in~~
419 ~~eucalypt~~eucalypt and pine woodland, by hindering infiltration, ~~can cause lower soil~~
420 ~~moisture~~ (Dekker and Ritsema, 1994; Doerr and Thomas, 2000), ~~might also possibly~~help to
421 ~~explaining the lower soil moisture results recorded in woodland-sandstone compared with~~
422 ~~limestone when changing~~ at times of transition from dry to wet conditions (15/10/2010 and
423 02/11/2011). ~~The weak, albeit significant correlation found between hydrophobicity and~~
424 ~~soil moisture can be attributed to spatial heterogeneity and the unavoidable separation of~~
425 ~~hydrophobicity and moisture measurement points (since ethanol drops would affect~~
426 ~~moisture content):~~

427 Despite the inverse correlation found between hydrophobicity and soil moisture content in
428 the woodland units, no soil moisture threshold seems to determine the switching pattern
429 between hydrophobic and hydrophilic soil properties. This accords with Previous studies
430 elsewhere also showed the inconsistent results recorded elsewhere. and denoted that the
431 existence of a threshold may be illusive, despite useful to understand hydrophobicity and
432 their potential impacts on hydrological processes. Thus in field experiments in Portugal,
433 Leighton-Boyce et al. (2005) reported no threshold for up to 50% soil moisture content,
434 whereas Doerr and Thomas (2000) found one at 28%. Reports of thresholds outside
435 Portugal vary from 21% for medium-textured soils in SE Spain (Soto et al., 1994), to 38%
436 for Dutch clayey peats (Dekker and Ritsema, 1994) and 50% for some organic-rich
437 Swedish soils (Berglund and Persson, 1996).

438 The seasonal changes lower water affinity provided by greatest in hydrophobicity of
439 woodland areas would explain seasonal contrast in could have led to limited infiltration
440 capacity during dry periods. Thus, under driest conditions, when hydrophobicity is
441 widespread on woodland soil, and measured infiltration capacity was minimal, whereas:
442 However, in wettest conditions, the limited spatial extent of hydrophobicity allowed
443 infiltration capacity of woodland sites to attain the highest values within *Ribeira dos*
444 *Covões*. Nevertheless, the low inverse correlation coefficient found between infiltration
445 capacity and hydrophobicity, despite being statistically significant, may have arisen
446 because infiltration sometimes may sometimes have been is delayed by repellency, but on
447 other occasions have commenced with switching to hydrophilic conditions by the end of
448 the final 10 minutes of the and the soil may not have reached steady state infiltration rate
449 conditions after 30 minutes measurement period.

450 Organic matter arguably plays a dual role in explaining seasonal contrast in infiltration
451 capacity in woodland units. Thus, although it is associated with hydrophobic conditions and
452 low infiltration capacities in dry and transitional weather, in wet periods in winter, when
453 hydrophobicity has largely disappeared, the same high θ levels of organic matter -is usually
454 promote-associated with structured soils of high matrix infiltration capacity, representing
455 the more typical situation of forest soils (e.g. Costa, 1999; Mouri et al., 2011.).
456 Nevertheless, with hydrophobicity banishment through autumn and winter seasons, as a
457 result of increasing rainfall, matrix infiltration capacity of woodland areas raised, attaining
458 the highest values in January, and denoting the high permeability usually associated with
459 forest soils (Mouri et al., 2011).

460 The variations in hydrophobicity, soil moisture and infiltration capacity linked to geological
461 and land-use controls and seasonal climatic influences discussed above result in
462 spatiotemporal patterns of overland flow that differ seasonally and between woodland-
463 sandstone and woodland-limestone areas. In storms following summer dry periods (e.g
464 following 30/09/2010 and 13/06/2010), drought-induced hydrophobicity in
465 eucalyptuseucalypt and pine areas and resultant very low matrix infiltration capacity makes
466 the woodland-sandstone areas particularly susceptible to infiltration-excess overland flow
467 generation. -The less hydrophobic nature of the predominantly oak vegetation of woodland-
468 limestone areas means that they are less prone to infiltration-excess overland flow.

469 Following dry periods (30/09/2010 and 13/06/2010), soil dryness was widespread and
470 hydrophobicity was dominant and most severe mainly in woodland and agricultural
471 limestone areas, because of vegetation density and type. Drought induced hydrophobicity
472 promoted very low matrix infiltration capacity, making these landscape units susceptible to

473 ~~infiltration excess overland flow generation in succeeding rainstorms. In urban and~~
474 ~~agricultural sandstone areas, greater infiltration capacity under the same conditions (Figure~~
475 ~~10) made these areas overland flow sinks. In woodland and agricultural limestone areas,~~
476 ~~however,~~ Prolonged or repeated rainfall events lead to partial switching of woodland soils
477 to a hydrophilic state, and reductions in hydrophobicity severity and spatial extent and
478 severity of hydrophobicity, and enhancement of infiltration capacity. Hydrophobicity in
479 eucalyptus eucalypt stands is more resistant to break down, requiring longer and/or a greater
480 number of rainfall events. Because of this, infiltration capacity generally remained low in
481 woodland sandstone areas (Figure 9a), and therefore prone to generate overland flow during
482 transitions from dry to wet conditions, as recorded on 15th October 2010 (Figure 9). In
483 prolonged wet weather of the winter wet season, hydrophobicity largely disappeared even
484 in woodland-sandstone areas, and no infiltration-excess overland flow occurred. –Even
485 under the wettest winter conditions, woodland areas showed relatively low soil moisture
486 and high infiltration capacities and saturation overland flow was rare.

487
488 In prolonged wet weather, hydrophobicity disappeared and infiltration capacity increased
489 even in woodland.

490 The potential for infiltration-excess overland flow in urban and woodland landscape
491 units soils in dry summer conditions was confirmed by rainfall simulation experiments,
492 performed in the study area, but not on agricultural soils. Hour-long experiments simulating
493 when a 43 mm h⁻¹ simulated rainfall (a typical maximum reached over several years) in a
494 small plot (0.25m²) produced runoff coefficients of of 59-99% on wettable urban soils

495 ~~(slope: 6-30°), 20-83% in a small plot (0.25 m²) in extremely hydrophobic woodland~~
496 ~~(slope: 5-36°), but 0% on wettable agricultural land (slope 15-50°) (Ferreira et al., 2012eb).~~
497 ~~Under natural rainfall, however, in larger runoff plots (16m²) in woodland, however,~~
498 ~~installed in woodland areas showed that even under extremely hydrophobic conditions,~~
499 ~~overland flow did not exceed 3% even for a 23mm rainfall event (Ferreira et al., 2012a),~~
500 ~~mainly because of. High water infiltration bypassing the in a hydrophobic soil matrix may~~
501 ~~be explained by preferential flow via macropores that can be provided by, for example,~~
502 ~~root-holes, invertebrate activity and high concentrations of stones (e.g. Urbanek and~~
503 ~~Shakesby, 2009; Hardie et al., 2011). Such bypass (preferential) flow and is viewed as an~~
504 ~~important mechanism not only in both extremely hydrophobic soils (Doerr and Thomas,~~
505 ~~2000), but also in dry loamy soils with high clay and silt contents (Yang and Zhang, 2011;~~
506 ~~Bracken and Croke, 2007). Cracks in clay soils were observed in dry conditions during~~
507 ~~fieldwork in the catchment study.~~
508 ~~Nevertheless, in Ribeira dos Covões, even under the wettest winter conditions, woodland~~
509 ~~areas showed relatively low soil moisture and high infiltration capacities, indicating their~~
510 ~~potential to act as sinks in absorbing overland flow from upslope.~~

511 **5.21.2. Urban landscape units**

512 ~~In contrast Opposing to woodland, soil areas of urban landscape units environments in the~~
513 ~~Ribeira dos Covões catchment are characterized by lowest soil organic matter content.;~~
514 ~~This is probably, possibly linked to the reduced and patchy vegetation cover and, in some~~
515 ~~locations, either loss or deposition of surface soil and/or deposition of mineral soil. The~~
516 ~~higher Greater bulk density was observed, most likely may be largely due to compaction by~~
517 ~~people human trampling and vehiclelesular traffic (Silva et al., 1997), as a result of vehiclelear~~

518 access and parking in the discontinuous urban fabric. Soil bulk densities measured in urban
519 areas (1.07-1.72 g cm⁻³) were similar to those (1.19-1.62 g cm⁻³) reported in Nanjing,
520 China of 1.19-1.62 g cm⁻³ in different urban functional zones where lowest minimum values
521 were recorded in greenbelt areas and maximum ones in parking zones (Yang and Zhang,
522 2011).

523 In the Ribeira dos Covões catchment, urban areas were the dominance of bare
524 surfaces or reduced and sparse grass and sparse shrub vegetation. This reduced vegetation
525 cover is likely to foment is the main cause of the recorded widespread hydrophilic
526 conditions throughout over the year. Only at particularly in the well vegetated sites was
527 hydrophobicity recorded was observed during the driest periods. Bare soil sites, such as in
528 the urban landscape units, mainly found on sandstone, being more is also susceptible to
529 evaporation (Nunes et al., 2011), which may have led to the low soil moisture content
530 recorded ; particularly during in dry-wet the transitional periods, such as between dry and
531 wet settings (for example, in the southwest SW of the catchment between on 02/11/2010
532 and 21/03/2011; (Figure 8). On the other hand, the minor rainfall interception during storms
533 would enhance soil moisture content over wet conditions.

534 The generally hydrophilic conditions found in over urban soil environments would help to
535 explain favour the high soil matrix infiltration capacity values is ty and may explain the great
536 values recorded particularly after prolonged dry weather over dry settings (Figure 9),
537 despite. High infiltration capacity of the urban soils was not expected considering the upper
538 the high bulk density, ; despite no significant correlation was found between both variables,
539 which elsewhere has been noted to be associated with Lower infiltration capacities y
540 associated with higher bulk density linked to urban activities has been noted elsewhere (e.g.

541 Dornauf and Burghardt, 2000; Yang and Zhang, 2011). Nevertheless, with increasing soil
542 moisture content over the wet periods, The very low and in some cases zero values of soil
543 matrix infiltration capacity was reduced and attained even null values in few spots.
544 recorded Decreasing infiltration capacity under during wet periods wet setting is because
545 of may be linked to a decline in the suction force and then saturation of the often thin soil
546 (Costa, 1999). The inverse correlation recorded between soil moisture and infiltration
547 capacity for urban soils these variables was also found reported in Tasmania, Australia,
548 where the application of dye tracer in low antecedent soil moisture showed infiltration to an
549 average depth of 1.03 m (with a wetting front velocity of 1160 mm h⁻¹) in low antecedent
550 soil moisture conditions, compared with a depth of 0.35 m (and a wetting front velocity of
551 120 mm h⁻¹) with wet antecedent conditions (Hardie et al., 2012).

552 In urban landscape units, overland flow is readily generated on paved and tarmac
553 impervious surfaces, but for urban soils it varies in importance both seasonally and between
554 urban-sandstone and urban-limestone areas. In dry summer conditions, the generally
555 hydrophilic soils of greater infiltration capacity –(Figures 9 and 10) lead to little or no
556 overland flow and make these areas overland flow sinks. In contrast, after larger winter
557 storm events, soil saturation or near-saturation was identified at urban-limestone sites
558 (Figures 7 and 8), associated with a near-surface water table (on the valley floor) and
559 shallow soils of low water storage capacity (on hillslopes). In both situations saturation
560 overland flow was at least locally being generated. In contrast, in urban soils on sandstone,
561 soil moisture levels recorded in winter were much lower than on limestone (Figure 7) and
562 infiltration capacities (Figure 9) varied from low (on bare soil) to relatively high (on

563 uncompacted, vegetated sites); the result was patchy Hortonian overland flow, mostly on
564 the bare soil areas, with some of the vegetated patches acting as overland flow sinks.

565 Easton et al. (2007), in different land uses with permeable soil, also found higher runoff
566 coefficients on shallow soils, and Buttle et al. (2004) considered soil thickness to be the
567 most important control on runoff delivery, and stated that slopes with average soil
568 thicknesses of <0.2 m consistently produced overland flow once surface storage capacity
569 was achieved.

570 The potential for infiltration-excess overland flow generation in urban and woodland soils
571 was demonstrated by runoff coefficients of 59-99% recorded on hydrophilic urban soils
572 (slope: 6-30°) in confirmed by rainfall simulation experiments performed in the study area,
573 but not on agricultural soils. Hour long experiments simulating a 43 mm h⁻¹ rainfall
574 simulations (a typical maximum reached over several years) in a on small plots (0.25m²) at
575 the field sites, though it was unclear whether the overland flow was infiltration-excess or
576 saturation excess saturation in nature produced runoff coefficients of 59-99% on wettable
577 urban soils (slope: 6-30°), 20-83% in extremely hydrophobic woodland (slope: 5-36°), but
578 0% on wettable agricultural land (slope 15-50°) (Ferreira et al., 2012b).

Formatted: Space After: 2.4 line

579 5.1.3 Agricultural landscape units

580 In agricultural landscape units areas, different ~~st~~land-use/land management types lead
581 to ~~im~~print major differences on surface cover and soil properties. The ~~A~~gricultural
582 types ~~fields~~ on ~~over~~laying sandstone ~~include~~ (mainly pasture, small gardens and olive ~~tree~~
583 plantations). ~~This~~ agricultural practices may explain the low organic matter content and ~~the~~

584 high bulk density results of that landscape unit compared with the agricultural-limestone
585 unit, where ~~when compared with the contrasting~~ abandoned fields undergoing natural vegetation
586 ~~succession are; dominant, on limestone, with vegetation following the natural succession.~~
587 This greater vegetation cover with higher soil organic matter content for ~~under~~ agricultural-
588 limestone would also explain the unit's enhanced ~~hydrophobic properties, linked to higher~~
589 ~~spatial extent and severity than on sandstone~~ agricultural sandstone soils.
590 ~~Nevertheless~~ However, considering the lower vegetation cover and the dominance of more
591 ~~Mediterranean herbaceous and scrub species,~~ hydrophobicity at ~~in~~ agricultural-limestone
592 sites was ~~less~~ not so severe as ~~than~~ in woodland, and fewer ~~less~~ rainfall events were required
593 to accomplish ~~stimulate the switching pattern between~~ from hydrophobic to ~~and~~ hydrophilic
594 ~~conditions~~ characteristics, and ~~In agricultural limestone fields, the~~ hydrophobicity re-
595 establishment ~~during~~ wet to dry transitions was also slower than for woodland (Figure 5).
596 In a previous study of a partly urbanized Mediterranean catchment, Fernández and Ceballos
597 (2003) only recorded lower hydrophobicity ~~persistence~~ stability when conditions were
598 changing from dry to wet.

599 ~~In~~ The generally, ~~agricultural areas showed~~ greater soil moisture values ~~content of~~
600 ~~agricultural~~ when compared with ~~the~~ other landscape units ~~land uses~~, despite the
601 ~~absence~~ lack of irrigation, ~~This~~ may be explained by the lower vegetation cover of the
602 agricultural-limestone sites and the low hydrophobicity, particularly when compared with
603 woodland. In addition, high surface roughness ~~associated with tillage in~~ agricultural-
604 sandstone fields, ~~mostly favoured by tillage practices,~~ may enhance surface water retention
605 and lead to higher soil moisture (Álvarez-Mozos et al., 2009), especially when compared
606 with ~~untilled~~ urban soils.

607 Soil moisture, however, was ~~only~~ slightly higher at agricultural-limestone than agricultural-
608 sandstone sites, despite most of the former being abandoned. This ~~may be could possibly be~~
609 ~~a consequence of the marly nature of the limestone, which leads to soil properties~~
610 ~~differences, coupled with~~ greater fractions of fine material. ~~in agricultural limestone areas.~~
611 ~~Furthermore, That~~ However, the small soil moisture difference is ~~small~~ may reflect the fact
612 ~~that~~ most sandstone agricultural sites are on valley floors (Figure 8), whereas limestone
613 sites are mainly on upper slopes, where the soil is shallow (generally <40cm depth), though
614 ~~in the wettest periods some saturation was observed here.~~

615 Differences in particle size distribution and land management practices, particularly
616 wheeling, may explain higher soil porosity on abandoned limestone than on ploughed
617 sandstone fields. Nevertheless, coarser particle size distribution and minor hydrophobicity
618 ~~is likely to provide may explain~~ greater soil matrix infiltration capacity on sandstone
619 compared with limestone agricultural areas ~~in dry periods.~~

620 However, rising soil moisture content through the wet season, could restrict soil matrix
621 infiltration capacity over agricultural areas, mostly noticed on sandstone fields. In
622 agricultural-limestone sites, matrix infiltration capacity was relatively constant over the
623 year. In this landscape unit, the slight infiltration capacity increase during early autumn,
624 possibly due to soil hydrophobicity shrinkage, gives place to a decreasing capacity in later
625 autumn and winter seasons, as a result of soil moisture increase. Throughout spring, with
626 soil moisture decrease, infiltration capacity tend to increase, but possibly with
627 hydrophobicity re-emergence, infiltration capacity was limited again. The development of
628 hydrophobic conditions in the agricultural soils was clearly slower than woodland (Figure
629 5).

630 Overland flow generation, in response to the contrasts in soil moisture, hydrophobicity and
631 infiltration capacity and their seasonal dynamics discussed above, differed between the
632 agricultural-sandstone and agricultural-limestone landscape units. In agricultural-sandstone
633 areas, high infiltration capacities associated with hydrophilic soils throughout the year and
634 with sandy particle size meant that overland flow was absent in summer and in winter was
635 only generated in big events or following very wet weather. In contrast, the greater
636 vegetation of the abandoned fields on limestone led to hydrophobic soils in summer and a
637 degree of proneness to infiltration-excess overland flow. Despite partial switching in
638 transition periods and total switching to hydrophilic conditions in winter wet periods, the
639 relatively low infiltration capacities and high soil moisture resulting from the marly
640 limestone lithology meant that the agricultural limestone areas were more prone in winter to
641 saturation overland flow than the sandstone areas.

642 ~~but in urban limestone and agricultural areas. Increased soil moisture led to reduced~~
643 ~~infiltration capacity, enhancing their potential to generate Hortonian overland flow. After~~
644 ~~larger winter storm events, soil saturation or near-saturation was identified at a few~~
645 ~~agricultural sandstone and urban limestone sites and at one woodland sandstone spot~~
646 ~~(Figure 9), associated with a near-surface water table (on the valley floor) and shallow soils~~
647 ~~of low water storage capacity (on hillslopes). Easton et al. (2007), in different land uses~~
648 ~~with permeable soil, also found higher runoff coefficients on shallow soils, and Buttle et al.~~
649 ~~(2004) considered soil thickness to be the most important control on runoff delivery, and~~
650 ~~stated that slopes with average soil thicknesses of <0.2 m consistently produced overland~~
651 ~~flow once surface storage capacity was achieved.~~

652 ~~The potential for~~ Unlike on urban and woodland soil sites, no infiltration-excess overland
653 ~~flow in urban and woodland soils was confirmed by~~ was recorded in 43 mm h⁻¹ rainfall
654 ~~simulation experiments performed in the study area, but not on agricultural soils. Hour long~~
655 ~~experiments simulating a 43 mm h⁻¹ rainfall (a typical maximum reached over several~~
656 ~~years) in a small plot (0.25m²) produced runoff coefficients of 59-99% on wettable urban~~
657 ~~soils (slope: 6-30°), 20-83% in extremely hydrophobic woodland (slope: 5-36°), but 0% on~~
658 ~~wettable on hydrophilic agricultural land (slope 15-50°) in the study area (Ferreira et al.,~~
659 ~~2012eb).~~

660 ~~Generally, infiltration capacity was significantly correlated with hydrophobicity and soil~~
661 ~~moisture, but the lower correlation coefficients may be because infiltration capacity was~~
662 ~~only calculated during the last 10 minutes, and hydrophobicity and soil moisture were~~
663 ~~measured separately on adjacent soil. Nevertheless, Principal Component Analysis (PCA)~~
664 ~~showed that despite the complex interaction between hydrophobicity and soil moisture,~~
665 ~~these variables together explain 63% of total infiltration capacity variance (Table 2). When~~
666 ~~particle size characteristics (surface and subsurface coarse sand and silt fractions, and~~
667 ~~subsurface clay) and organic matter content (surface and subsurface) are considered, the~~
668 ~~three component variables together explain 76% of infiltration variance (Table 3).~~
669 ~~However, the results of PCA must be interpreted as only indicative, since the variables do~~
670 ~~not follow the normal distribution that is strictly required by the approach.~~

671 **5.1.4 Synthesis: the influences of lithology, topography and land-use factors on**
672 **overland flow and temporal variation in its distributioneontrols within the Ribeirão**
673 **dos Covões catchment**

674 Lithology seems to play an important role in controlling spatiotemporal dynamics of
675 overland flow in the Ribeirão dos Covões catchment via its influence on particle size
676 distribution, which may explain soil moisture and infiltration capacity variability over the
677 catchment. Generally, the greater sand fractions and deeper soils of the sandstone areas,
678 characterized by greatest sand fractions, provide limited water storage capacity, linked to
679 lower soil moisture content, and promote greater infiltration capacity and water storage
680 capacity, and lower soil moisture, leading to reduced proneness to both Hortonian and
681 saturation overland flow. In contrast, the other hand, the higher silt-clay content and
682 shallower nature of soils on the marly limestone exposed result in greater soil moisture, and
683 lower infiltration and water storage capacities and hence greater proneness to saturation
684 overland flow than on sandstone, possibly due to higher silt and clay, because of the marly
685 limestone nature, and shallower depth of the soils. These are in line with reports elsewhere
686 of the influence of shallow soils (Easton et al., 2007, Hardie et al., 2011) and variations in
687 particle size. Infiltration capacity enlargement with decreasing clay and increasing sand
688 contents have also been reported elsewhere (Rahardjo et al., 2008; Yang and Zhang, 2011)
689 on overland flow. Reduced infiltration capacity with increasing clay content may be due not
690 only to its expansion properties but also to surface crust development under dry conditions
691 (Yang and Zhang, 2011). However, lithology had no consistent effect on organic matter,
692 bulk density and soil porosity.

693 Secondly local topographic characteristics also seem to be an important driver. Saturation
694 was observed at urban soil sites near streams (Figure 8) caused either by (1) lateral
695 subsurface flows from upslope (Aryal et al., 2005) or (2) groundwater table rise, as
696 recorded at a woodland-sandstone site near to an active spring on 24th January 2011 (Figure
697 8). In a small cultivated Mediterranean catchment, Latron and Gallart (2007), also

698 explained the saturation pattern with extent and height of the water table. The locations and
699 extents of the wettest areas in the *Ribeira dos Covões* catchment varied temporally, a
700 feature also reported elsewhere within agricultural hillslope (Walter et al., 2000) and mixed
701 agricultural and forested (Easton et al., 2007) areas.

702
703 Land-use and land management constitutes the third and perhaps most important influence
704 on differences in overland flow between and within landscape units. This influence is
705 exerted through the effects of different percentage ground covers, management practices
706 and other human activities on degrees of soil compaction, soil moisture levels and soil
707 permeability and via the effects of different plant species on hydrophobicity severity,
708 switching dynamics and seasonality. ~~In fact, these soil properties seems to be particularly~~
709 ~~affected by the land use and management practices, which lead to the division of the l~~
710 Overland flow is consequently of greatest significance in urban landscape units, particularly
711 in winter, when urban soils are often either saturated or bare and compacted, whereas in
712 summer overland flow from impervious or bare areas is reduced by hydrophilic soil
713 patches. -Overland flow in the woodland units is in general greatly reduced by vegetation
714 effects on infiltration, but is seasonally enhanced in storms following summer dry periods
715 in ~~eucalypt~~eucalypt and pine woodland-sandstone areas because of their severe soil
716 hydrophobicity, but absent in woodland-limestone areas because of the oak woodland land-
717 use. The agricultural-sandstone landscape unit produces very little overland flow because of
718 high infiltration capacities resulting from a combination of land-use and land management
719 practices that do not result in compaction, but mostly because of the sandy soils. In
720 converse fashion, the abandoned field land-use of agricultural-limestone areas probably has

721 the effect of reducing overland flow responses from what they would otherwise be with
722 active cultivation, but which for lithology-related reasons can be significant particularly in
723 winter wet weather.

724 Differences in temporal variability of soil hydrological properties between landscape units
725 led to spatial fluctuation in overland flow sources and sinks. In wet winter conditions,
726 overland flow is greatest from the urban landscape units and also significant from the
727 agricultural-limestone unit, but comparatively little from the hydrophilic and permeable
728 agricultural-sandstone and woodland units except in the wettest weather. —During
729 transitions from wettest to dry conditions, the spatial pattern of response to rainstorms is
730 reversed, with decreasing susceptibility to ~~saturation-excess~~ saturation overland flow as soil
731 moisture declined (mainly associated with agricultural- and urban-limestone areas) and
732 increasing vulnerability to infiltration-excess overland flow, enhanced by hydrophobicity
733 re-establishment (particularly in woodland but also on agricultural-limestone). — In
734 summer, overland flow is comparatively low but still greatest in urban-limestone areas and
735 to a lesser extent is also significant in the woodland and agricultural-limestone units
736 because of their hydrophobic condition, but urban-sandstone and agricultural-sandstone
737 areas produce comparatively little overland flow, because of locally or more widespread
738 hydrophilic and permeable surface soils providing overland flow sinks. Finally, in the dry
739 to wet transition of autumn, patterns of overland flow are broadly similar to the wet-to-dry
740 transition, with hydrophobicity (and overland flow responses) becoming most rapidly re-
741 established in ~~eucalypt~~ eucalypt parts of the woodland-sandstone landscape unit.

742 Spatial variability of soil properties within the same landscape unit, such as particle size
743 and hydrophobicity, provides heterogeneous infiltration capacities, where this particularly

744 ~~applies to the partly bare urban-sandstone unit and woodland and agricultural-limestone~~
745 ~~units in transitional periods~~ ~~-(Figure 9). Soil spots with matrix infiltration capacity lower~~
746 ~~than rainfall intensity will lead to infiltration-excess overland flow, which may be~~
747 ~~infiltrated in surrounding soil spots with greater infiltration capacity. Only the few most~~
748 ~~permeable soil patches found in the landscape units could cope with a rainfall intensity of~~
749 ~~5.4 mm h⁻¹, the mean hourly rainfall intensity of storm events ≥5mm recorded in the years~~
750 ~~2010-2011. Not all the landscape units provided spots with sufficient permeability~~
751 ~~throughout the year. Urban and agricultural landscape units showed more sites of high~~
752 ~~permeability after dry periods, while even in wettest conditions, woodland provided sites of~~
753 ~~high infiltration capacity. The generally higher permeability of sandstone than limestone~~
754 ~~areas highlights the former's lower potential for infiltration-excess overland flow~~
755 ~~generation. Nevertheless, even the most permeable soil patches could not cope with the~~
756 ~~maximum rainfall intensity of 15.6 mm h⁻¹ recorded in the rainstorm of 2nd November 2011.~~
757 ~~Thus infiltration-excess overland flow would be expected to occur widely during~~
758 ~~particularly intense storms in all landscape units.~~

759

760 ~~andscape units in two groups: (1) woodland areas on both sandstone and limestone and~~
761 ~~agricultural limestone sites, and (2) urban soils and agricultural sandstone sites, both~~
762 ~~subject to more human pressure than the first group.~~

763 ~~Despite the spatiotemporal variability as regards to the land-use and lithology impacts on~~
764 ~~soil moisture, local topographic characteristics seems to be an important driver. Saturation~~
765 ~~was observed at urban soil sites near streams (Figure 8) caused either by (1) lateral~~
766 ~~subsurface flows from upslope (Aryal et al., 2005) or (2) groundwater table rise, as~~

767 ~~recorded at a woodland sandstone site near to an active spring on 24th January 2011~~
768 ~~(Figure 8). In a small cultivated Mediterranean catchment, Latron and Gallart (2007), also~~
769 ~~explained the saturation pattern with extent and height of the water table. The locations and~~
770 ~~sizes of the wettest areas in the Ribeira dos Covões catchment varied temporally, a feature~~
771 ~~also reported elsewhere within agricultural hillslope (Walter et al., 2000) and mixed~~
772 ~~agricultural and forested areas (Easton et al., 2007).~~

773

774 ~~The variable soil organic matter in woodland may be due to different tree types and~~
775 ~~management affecting the litter layer thickness. Eucalyptus Eucalypt-dominated areas~~
776 ~~tended to have relatively low organic matter, possibly reflecting periodic understory~~
777 ~~clearance to help prevent wildfires but also low understorey vegetation caused by reduced~~
778 ~~water availability (DeBano, 2000). Lower soil organic matter on pasture, small gardens and~~
779 ~~olive tree plantations on sandstone than on agricultural limestone soils may reflect the~~
780 ~~effect of agricultural practices. The very low organic matter contents recorded for urban~~
781 ~~soils may be linked to their reduced vegetation cover and, in some locations, loss of surface~~
782 ~~soil and/or deposition of mineral soil.~~

783 ~~Vegetation and its root system are also linked to lower soil bulk density, notably in~~
784 ~~woodland and abandoned agricultural limestone fields. The higher bulk density of~~
785 ~~agricultural sandstone and urban soils is most likely due to vehicular traffic (Silva et al.,~~
786 ~~1997), linked to wheeling in agricultural fields and human trampling as well as car access~~
787 ~~and parking in the discontinuous urban fabric. Soil bulk densities in urban areas (1.07-1.72~~
788 ~~g cm⁻³) were similar to those reported in Nanjing, China, of 1.19-1.62 g cm⁻³ in different~~
789 ~~urban functional zones, where minimum values were recorded in greenbelt areas and~~

790 maximum ones in parking areas (Yang and Zhang, 2011). Reduced bulk density was
791 reported in soils with greater organic matter, since it helps the formation of soil aggregates
792 and structure (Celik et al., 2010).

793 In woodland and urban soils, lithology had no consistent effect on organic matter, bulk
794 density and soil porosity. Land management, particularly tillage, however, may explain
795 higher soil porosity on abandoned limestone than on ploughed sandstone fields.

796 Despite rock fragment and particle size distribution not varying significantly between
797 landscape units, considering organic matter, bulk density and soil porosity together, two
798 landscape unit groups can be identified: (1) woodland areas on both sandstone and
799 limestone and agricultural limestone sites, and (2) urban soils and agricultural sandstone
800 sites, both subject to more human pressure than the first group.

801

802 **5.1.2 Soil hydrophobicity**

803

804 Extensive hydrophobic areas in summer and widespread disappearance in winter accords
805 with previous studies (e.g., Dekker and Ritsema, 1994; Doerr et al., 2000; Martínez-Zavala
806 and Jordán López, 2009), but landscape units showed considerable differences both in
807 hydrophobicity extent and switching speed during dry to wet transition periods and *vice*
808 *versa*. In contrast, in a previous study of a partly urbanized Mediterranean catchment,
809 Fernández and Ceballos (2003) only recorded lower hydrophobicity stability when
810 conditions were changing from dry to wet.

811 Vegetation density and type is apparently important in accounting for differences in
812 spatiotemporal patterns of hydrophobicity, with woodland far more hydrophobic than urban

813 | ~~areas, where mostly only well vegetated sites in the driest periods were affected. On~~
814 | ~~sandstone, release of resins, waxes and aromatic oils (Doerr et al., 1998; Jordán et al., 2008)~~
815 | ~~in eucalyptuseucalypt woodland is thought to have caused hydrophobicity to be more~~
816 | ~~extensive and resistant to break down than in pine stands (Figure 5a). Hydrophobicity,~~
817 | ~~particularly in eucalyptuseucalypt stands, was able to persist following rainfall of as much~~
818 | ~~as 200mm in 2 months (Ferreira, 1996; Doerr and Thomas, 2000). It was less severe and~~
819 | ~~easier to break down in the woodland limestone areas because oak, not usually associated~~
820 | ~~with hydrophobic soil (Zavala et al., 2009), is the dominant vegetation.~~

821 | ~~Vegetation type can influence hydrophobicity re-establishment after rainfall by affecting~~
822 | ~~the input of water repellent substances (Doerr and Thomas, 2000; Hardie et al., 2012). The~~
823 | ~~rate of re-establishment would depend on the biological productivity of the ecosystem~~
824 | ~~(Doerr and Thomas, 2000), which depends on the biological productivity of the ecosystem~~
825 | ~~(Doerr and Thomas, 2000), the type of hydrocarbon substances produced and microbial~~
826 | ~~activity (Keizer et al., 2008). This may explain the rapid re-establishment on woodland,~~
827 | ~~particularly in eucalyptuseucalypt and pine stands, although Santos et al. (in press) report~~
828 | ~~greater dynamism, and more frequent hydrophobic conditions, in eucalypt than in pine.~~

829 | ~~The positive correlation found between hydrophobicity severity and organic matter content~~
830 | ~~tallies with findings elsewhere (e.g. Dekker and Ritsema, 2000), but organic matter type~~
831 | ~~and quality are more important than amount as demonstrated by the differences between~~
832 | ~~woodland species. The correlation, although weak, found between hydrophobicity and~~
833 | ~~sand fraction is similar to that found in other studies (e.g. DeBano, 1991; McKissock et al.,~~
834 | ~~2000), although finer textured soils also be hydrophobic (e.g. Doerr and Thomas, 2000).~~

835 The weak, albeit significant correlation found between hydrophobicity and soil moisture is
836 attributed to spatial heterogeneity and the unavoidable separation of hydrophobicity and
837 moisture measurement points (since ethanol drops would affect moisture content). Many
838 studies have reported low water contents corresponding to high hydrophobicity persistence
839 and severity and *vice versa*, but defining a universal soil moisture 'switching' threshold has
840 proved elusive. In field experiments in Portugal, Leighton Boyce (2002) reported no
841 threshold for up to 50% soil moisture content, whereas Doerr and Thomas (2000) found
842 one at 28%. Reports of thresholds outside Portugal vary from 21% for medium textured
843 soils in SE Spain (Soto et al., 1994), to 38% for Dutch clayey peats (Dekker and Ritsema,
844 1994) and 50% for some organic rich Swedish soils (Berglund and Persson, 1996).

845

846 **5.1.3 Soil moisture**

847 Generally, limestone showed greater soil moisture than sandstone, possibly due to higher
848 silt and clay, because of the marly limestone nature, and shallower depth of the limestone
849 soils (Easton et al., 2007, Hardie et al., 2011).

850 Landscape units all had similarly low soil moisture contents in long, dry periods, but
851 differed most during transitional periods. At these times, soil moisture was low in urban
852 soils, mainly on sandstone, probably due to bare surfaces or reduced mainly grass and
853 sparse shrub vegetation cover (for example, in the SW of the catchment between
854 02/11/2010 and 21/03/2011; Figure 8). Bare soil, such as urban, is susceptible to
855 evaporation (Nunes et al., 2011), while shading and ground vegetation and litter covers
856 provided by woodland reduces soil moisture loss in warm, sunny conditions. Vegetation,
857 however, also promotes higher transpiration and interception, the latter particularly

858 important in percentage terms in small rainfall events (Holden, 2008). Interception and
859 transpiration may explain the low soil moisture at woodland and agricultural sandstone
860 sites, particularly on 30th September 2010. Woodland is also usually associated with more
861 permeable soils (Mouri et al., 2011), causing slightly lower soil moisture than in the other
862 land uses, even on limestone (Figure 7). Moreover, hydrophobic conditions, by hindering
863 infiltration, can cause lower soil moisture (Dekker and Ritsema, 1994; Doerr and Thomas,
864 2000), possibly explaining lower woodland sandstone compared with limestone soil
865 moisture values in changing dry to wet conditions (15/10/2010 and 02/11/2011).

866 The higher overall soil moisture on agricultural land, despite the lack of irrigation on
867 abandoned fields, pastures or olive groves, is possibly linked to low hydrophobicity and
868 high surface roughness (Álvares Mozos et al., 2011) (especially on tilled soils). Soil
869 moisture, however, was only slightly higher at agricultural limestone than agricultural
870 sandstone sites, despite most of the former being abandoned. On the other hand, most
871 sandstone agricultural sites are on valley floors (Figure 8), whereas limestone sites are
872 mainly on upper slopes, where the soil is shallow (generally <40cm depth), though in the
873 wettest periods some saturation was observed here.

874 Saturation was also observed at urban soil sites near streams (Figure 8) caused either by (1)
875 lateral subsurface flows from upslope (Aryal et al., 2005) or (2) groundwater table rise, as
876 recorded at a woodland sandstone site near to an active spring on 24th January 2011 (Figure
877 8). In a small cultivated Mediterranean catchment, Latron and Gallart (2007), found a linear
878 relationship between saturated area extent and baseflow discharge, with water table height
879 also being important in explaining the saturation pattern. The locations and sizes of the
880 wettest areas in the *Ribeira dos Covões* catchment varied temporally, a feature also noted in

881 agricultural (Walter et al., 2000) and mixed agricultural and forested (Easton et al., 2007)
882 areas, both in New York State, USA.

883

884 **5.1.4 Infiltration capacity**

885 The lower infiltration capacities recorded at limestone than sandstone sites are probably due
886 to the marly higher clay and silt nature of limestone. An infiltration capacity increase with
887 sand content has also been reported elsewhere (Rahardjo et al., 2008; Yang and Zhang,
888 2011), while the reduction with increasing clay content may be due not only to its
889 expansion properties but also to surface crust development under dry conditions (Yang and
890 Zhang, 2011).

891 The variation in infiltration capacity values between landscape units and measurement dates
892 seems to reflect spatiotemporal variability of hydrophobicity and soil moisture. In dry
893 conditions, soil hydrophobicity restricted infiltration capacity at woodland and agricultural
894 limestone sites, whereas higher infiltration capacities (up to 12.9 mm h^{-1}) were reached on
895 urban and agricultural sandstone soils, mostly under hydrophilic and relatively weak
896 hydrophobic conditions that would have switched quickly during the infiltration capacity
897 experiments. After the first recorded rainfall events, on 15th October 2010, the considerable
898 decrease in hydrophobic severity at woodland limestone sites promoted increased
899 infiltration capacity, whereas the same rain had a more modest effect on agricultural
900 limestone and particularly woodland sandstone soils, due to hydrophobicity persistence
901 (Figure 9). Nevertheless, eventual switching during continued wet conditions led to
902 increased infiltration capacity, attaining 6.8 mm h^{-1} in woodland on 3rd January 2011.

903 ~~Conversely, on predominantly hydrophilic urban and agricultural sandstone sites, increased~~
904 ~~soil moisture throughout wet periods led to reduced or even zero infiltration capacities~~
905 ~~because of a decline in the suction force and then saturation of the soil. Infiltration capacity~~
906 ~~increased with decreased antecedent soil moisture. This was also found in Tasmania,~~
907 ~~Australia, where the application of dye tracer in low antecedent soil moisture showed~~
908 ~~infiltration to an average depth of 1.03 m (with a wetting front velocity of 1160 mm h^{-1})~~
909 ~~compared with a depth of 0.35 m (at a wetting front velocity of 120 mm h^{-1}) with wet~~
910 ~~antecedent conditions.~~

911 ~~The significant but not strong correlations with hydrophobicity and soil moisture may be~~
912 ~~because infiltration capacity was only calculated during the last 10 minutes, and~~
913 ~~hydrophobicity and soil moisture were measured separately on adjacent soil. In addition,~~
914 ~~since infiltration is delayed by repellency, the soil may not have reached steady state~~
915 ~~infiltration rate conditions after 30 minutes.~~

916 ~~Although organic matter is usually associated with structured soils of high infiltration~~
917 ~~capacity, in *Ribeira dos Covões* infiltration capacity was inversely related to organic matter~~
918 ~~content because of hydrophobicity. No significant correlation was found between~~
919 ~~infiltration capacity and bulk density, but there was some evidence of low individual values~~
920 ~~on urban soils attributable to higher bulk density. Lower infiltration capacity associated~~
921 ~~with higher bulk density linked to urban activities has been noted elsewhere (e.g. Dornauf~~
922 ~~and Burghardt, 2000; Yang and Zhang, 2011).~~

923 Principal Component Analysis (PCA) showed that despite the complex interaction between
924 hydrophobicity and soil moisture, these variables together explain 63% of total infiltration
925 capacity variance (Table 2). When particle size characteristics (surface and subsurface
926 coarse sand and silt fractions, and subsurface clay) and organic matter content (surface and
927 subsurface) are considered, the three component variables together explain 76% of
928 infiltration variance (Table 3). However, the results of PCA must be interpreted as only
929 indicative, since the variables do not follow the normal distribution that is strictly required
930 by the approach.

931

932 **Temporal fluctuations in overland flow over landscape units**

933 ~~Differences in temporal variability of soil hydrological properties between landscape units~~
934 ~~led to spatial fluctuation in overland flow sources and sinks. Following dry periods~~
935 ~~(20/09/2010 and 13/06/2010), soil dryness was widespread and hydrophobicity was~~
936 ~~dominant and most severe mainly in woodland and agricultural limestone areas, because of~~
937 ~~vegetation density and type. Drought induced hydrophobicity promoted very low matrix~~
938 ~~infiltration capacity, making these landscape units susceptible to infiltration excess~~
939 ~~overland flow generation in succeeding rainstorms. In urban and agricultural sandstone~~
940 ~~areas, greater infiltration capacity under the same conditions (Figure 10) made these areas~~
941 ~~overland flow sinks. In woodland and agricultural limestone areas, however, prolonged or~~
942 ~~repeated rainfall events led to partial switching, reductions in hydrophobicity severity and~~
943 ~~spatial extent, and enhancement of infiltration capacity. Hydrophobicity in~~
944 ~~eucalyptus eucalypt stands is more resistant to break down, requiring longer and/or a greater~~
945

946 ~~number of rainfall events. Because of this, infiltration capacity generally remained low in~~
947 ~~woodland sandstone areas, and therefore prone to generate overland flow during transitions~~
948 ~~from dry to wet conditions, as recorded on 15th October 2010 (Figure 9).~~

949 ~~In prolonged wet weather, hydrophobicity disappeared and infiltration capacity increased~~
950 ~~even in woodland, but in urban limestone and agricultural areas. Increased soil moisture led~~
951 ~~to reduced infiltration capacity, enhancing their potential to generate Hortonian overland~~
952 ~~flow. After larger winter storm events, soil saturation or near saturation was identified at a~~
953 ~~few agricultural sandstone and urban limestone sites and at one woodland sandstone spot~~
954 ~~(Figure 9), associated with a near surface water table (on the valley floor) and shallow soils~~
955 ~~of low water storage capacity (on hillslopes). Easton et al. (2007), in different land uses~~
956 ~~with permeable soil, also found higher runoff coefficients on shallow soils, and Buttle et al.~~
957 ~~(2004) considered soil thickness to be the most important control on runoff delivery, and~~
958 ~~stated that slopes with average soil thicknesses of <0.2 m consistently produced overland~~
959 ~~flow once surface storage capacity was achieved. Nevertheless, in *Ribeira dos Covões*, even~~
960 ~~under the wettest winter conditions, woodland areas showed relatively low soil moisture~~
961 ~~and high infiltration capacities, indicating their potential to act as sinks in absorbing~~
962 ~~overland flow from upslope. Any saturation overland flow produced on the valley floor,~~
963 ~~however, would remain at the surface until evaporated or the water table falls.~~

964 ~~During transitions from wettest to dry conditions, the spatial pattern of response to~~
965 ~~rainstorms is reversed, with decreasing susceptibility to saturation excess overland flow as~~
966 ~~soil moisture declined (mainly associated with agricultural and urban limestone areas) and~~
967 ~~increasing vulnerability to infiltration excess overland flow, enhanced by hydrophobicity~~
968 ~~re-establishment (particularly in woodland but also on agricultural limestone).~~

969 ~~Spatial variability of soil properties *within* the same landscape unit, such as particle size~~
970 ~~and hydrophobicity, provides heterogeneous infiltration capacities (Figure 9). Soil spots~~
971 ~~with matrix infiltration capacity lower than rainfall intensity will lead to infiltration excess~~
972 ~~overland flow, which may be infiltrated in surrounding soil spots with greater infiltration~~
973 ~~capacity. Only the few most permeable soil patches found in the landscape units could cope~~
974 ~~with a rainfall intensity of 5.4 mm h^{-1} , the mean hourly rainfall intensity of storm events~~
975 ~~$\geq 5 \text{ mm}$ recorded in the years 2010–2011. Not all the landscape units provided spots with~~
976 ~~sufficient permeability throughout the year. Urban and agricultural landscape units showed~~
977 ~~more sites of high permeability after dry periods, while even in wettest conditions,~~
978 ~~woodland provided sites of high infiltration capacity. The generally higher permeability of~~
979 ~~sandstone than limestone areas highlights the former's lower potential for infiltration~~
980 ~~excess overland flow generation. Nevertheless, even the most permeable soil patches could~~
981 ~~not cope with the maximum rainfall intensity of 15.6 mm h^{-1} recorded in the rainstorm of~~
982 ~~2nd November 2011. Thus infiltration excess overland flow would be expected to occur~~
983 ~~widely during particularly intense storms in all landscape units.~~

984 ~~The potential for infiltration excess overland flow in urban and woodland soils was~~
985 ~~confirmed by rainfall simulation experiments performed in the study area, but not on~~
986 ~~agricultural soils. Hour long experiments simulating a 43 mm h^{-1} rainfall (a typical~~
987 ~~maximum reached over several years) in a small plot (0.25 m^2) produced runoff coefficients~~
988 ~~of 59–99% on wettable urban soils (slope: $6–30^\circ$), 20–83% in extremely hydrophobic~~
989 ~~woodland (slope: $5–36^\circ$), but 0% on wettable agricultural land (slope $15–50^\circ$) (Ferreira et al.,~~
990 ~~2012c). Under natural rainfall, however, runoff plots (16 m^2) installed in woodland areas~~
991 ~~showed that even under extremely hydrophobic conditions, overland flow did not exceed~~
992 ~~3% even for a 23 mm rainfall event (Ferreira et al., 2012a). High water infiltration in a~~

993 ~~hydrophobic soil matrix may be explained by preferential flow via macropores provided by,~~
994 ~~for example, roots, invertebrate activity and high concentrations of stones (e.g. Urbanek~~
995 ~~and Shakesby, 2009; Hardie et al., 2011), and is viewed as an important mechanism in both~~
996 ~~extremely hydrophobic soils (Doerr and Thomas, 2000), but also in dry loamy soils with~~
997 ~~high clay and silt contents (Yang and Zhang, 2011; Bracken and Croke, 2007). Cracks in~~
998 ~~clay soils were observed in dry conditions during fieldwork in the catchment study.~~

999

1000 **5.23 Implications for catchment runoff delivery and land management**

1001 The changing nature of overland flow sources and sinks within the catchment can be
1002 expected to affect flow connectivity over the hillslope and influence storm runoff delivery
1003 to the stream network. Under hydrophobic conditions, infiltration-excess overland flow
1004 generated in relatively extensive woodland on steep slopes and on ~~small~~ shallow upstream
1005 agricultural-limestone soils, may reach the stream network directly or be delivered to the
1006 urban cores lying situated downslope (Figure 2b).

1007 Vegetation is widely considered as a key factor interrupting hydrological connectivity (e.g.
1008 Bracken and Croke, 2007; Appels et al., 2011). Greater vegetation interception provided by
1009 woodland and agricultural-limestone areas, compared with the other land-uses, tends to
1010 reduce overland flow , though the effect will be marginal in large storm events, when
1011 percentage interception is small. The more important effect of interception is in helping
1012 (together with transpiration) to reduce antecedent soil moisture levels prior to rainfall
1013 events~~However, greater vegetation interception provided by woodland and agricultural-~~
1014 ~~limestone areas, compared with the other land uses, reduces the amount of rainfall reaching~~
1015 ~~the ground, and thus, the susceptibility to generate overland flow, though the effect on~~

1016 ~~overland flow will be marginal in large storm events, when percentage interception is small.~~
1017 ~~The more important effect is helping (together with transpiration) to reduce antecedent soil~~
1018 ~~moisture levels prior to rainfall events.~~ In central Portugal, Valente et al. (1997) reported
1019 interception losses of 11% in ~~eucalypt~~*eucalypt* stands and 17% in *Pinus pinaster* forest, and
1020 ~~states stated~~ the ~~role influence~~ of a larger canopy storage ~~on greater rainfall interception, as~~
1021 ~~well as and~~ larger aerodynamic conductance on ~~increased evaporation water~~ losses. In
1022 addition, greater litter density ~~and frequency of root holes comparing compared~~ with the
1023 other landscape units, may lead to enhanced water interception, ~~and~~ retention ~~and~~
1024 ~~infiltration~~, particularly in smaller storm events after dry spells. ~~Despite enhancing water~~
1025 ~~losses, vegetation is widely considered as a key factor interrupting hydrological~~
1026 ~~connectivity (e.g. Braeken and Croke, 2007; Apples et al., 2011), beyond its positive~~
1027 ~~impact on soil properties, such as reduced bulk density, which enhanced soil infiltration~~
1028 ~~capacity.~~ Surface roughness also promotes water retention and reduces overland flow rates,
1029 and promotes discontinuities between overland flow source areas (Rodríguez-Caballero et
1030 al., 2012). ~~Greater interception, coupled with t~~These infiltration/retention processes
1031 operating at larger scales, as well as preferential flow ~~via root-holes and cracks~~,
1032 considerably reduce the risk that overland flow from low permeable soil sites might reach
1033 downslope contiguous urban areas and/or the stream network. Although the ~~higher~~
1034 ~~infiltration capacity of~~ urban soils may provide overland flow sinks, the ~~mainly~~
1035 impermeable ~~tarmac and paved~~ surfaces of urban areas ~~would~~ allow little infiltration,
1036 restricting the capacity to deal with rainfall and overland flow from upslope landscape
1037 units. Observations in *Ribeira dos Covões* over ~~three~~3 years suggest that only small
1038 amounts of overland flow were generated in woodland and agricultural limestone areas,
1039 mainly after dry conditions. ~~Nevertheless, preferential flow via macropores can reach~~

1040 | ~~streams relatively quickly, and thus contribute to the flood peak, as reported in~~
1041 | ~~Pennsylvania, USA (Yu et al., 2014).~~

1042 | Although not recorded during this study, clear-felling in woodland would cause increased
1043 | overland flow and water connectivity by providing bare, compacted areas and reducing
1044 | interception, transpiration and surface roughness. Thus the size and location of clear-felled
1045 | areas require planning to ensure that most overland flow is intercepted by downslope
1046 | woodland area sinks in order to reduce flood hazard. Clear-felling should also be timed to
1047 | avoid storms of early autumn rainy seasons, in view of the greater extent and location of
1048 | hydrophobic areas at that time (Figure 6). In addition, if forestwoodland managers select
1049 | tree species that release less hydrophobic substances, overland flow may be
1050 | correspondingly reduced (e.g. Ferreira et al. 2012a).

1051 | Under wet winter conditions, ~~saturation excess~~saturation overland flow becomes more
1052 | likely in urban and agricultural land-uses, but saturated areas may be more influenced by
1053 | topography and soil depth than by land-use (Figure 8). Overland flow generated in these
1054 | landscape units would be delivered mostly to the stream network, but also to downslope
1055 | woodland and urban cores in the case of upslope saturated shallow soils (Figures 2b and 8).
1056 | Previous studies reported higher runoff coefficients in shallow soils affecting hillslope
1057 | runoff connectivity (Kirkby et al., 2002; Easton et al., 2007; Hopp and McDonnell, 2009).
1058 | In agricultural fieldsareas, however, overland flow paths would depend on land
1059 | management. Land drains, ditches, wheel ruts and roads may enhance flow connectivity,
1060 | particularly if they are aligned downslope, whereas terracing and stone boundary walls can
1061 | form traps for water, enhancing infiltration and disrupting flow pathways. Overland flow
1062 | transfer from agricultural and urban areas to downslope woodland soils when hydrophilic

1063 may be dissipated by enhanced infiltration and surface retention. Furthermore, although
1064 much of the overland flow from impermeable urban surfaces located in upslope positions
1065 (Figure 2b) is collected by the urban drainage system and delivered directly into the stream,
1066 some flows into nearby soil.

1067 Because of the generally low infiltration capacity ~~or saturated condition of downslope~~
1068 ~~urban soil areas, saturation-excesssaturation~~ overland flow reaching ~~suchdownslope-urban~~
1069 areas may be problematic, although this can be offset by spatial differences in modified and
1070 unmodified soil properties providing a mosaic of varying infiltration capacity. Even if
1071 urban soils surrounding impermeable surfaces (e.g. roofs and roads) cannot act as sinks,
1072 ~~they may provide flow~~ obstructions ~~within them~~ (together such as with buildings and walls)
1073 ~~and so may~~ delay overland flow transfer. This will depend on urbanization style, since
1074 extended impermeable surfaces will enhance landscape connectivity, whereas detached
1075 houses surrounded by gardens and walls can provide sinks and flow discontinuity.

1076 The susceptibility of urban core areas located in topographic lows (Figure 2b) to ~~saturation-~~
1077 ~~excesssaturation~~ overland flow and stream flooding may represent a real flood hazard for
1078 the inhabitants, particularly considering the ~~recent~~ scale of ~~recent~~ urban consolidation ~~in the~~
1079 ~~Ribeira dos Coveões catchment~~. This risk may be enhanced by 1) additional overland flow
1080 resulting from greater connectivity with upslope areas subject to soil moisture increase and
1081 water table rise, and 2) the rapid transfer of most overland flow from upslope impermeable
1082 surfaces directly into the stream via the urban drainage system. These may be particularly
1083 important in larger storm events, considering the generally low soil permeability across the
1084 catchment. ~~Based on~~ ~~According to interviews with older citizens-interviews, f~~ ~~l~~ ~~o~~ ~~o~~ ~~d~~ ~~i~~ ~~n~~ ~~g~~
1085 ~~events-hazards~~ were already experienced ~~by older citizens which have reported flood events~~

1086 about 80, 50 and 10 years ago, when the urban area was considerably less extensive than
1087 ~~currently~~now.

1088 Analyses of storm hydrographs of the outlet stream (results not shown) suggest that the
1089 actual landscape mosaic of *Ribeira dos Covões* catchment, comprising extensive woodland
1090 areas and large urban areas near the catchment outlet, ~~together~~ with ~~numerous~~ smaller
1091 urban areas mainly along ridges ~~upslope with minor~~ and dispersed agricultural fields
1092 (Figure 2b), may be sufficient to promote discontinuities to the infiltration-excess overland
1093 flow generated by soil hydrophobicity. Thus, in dry settings, rainstorms of 2.8 mm
1094 (average) and 14.4 mm (large), recorded on 6th August and 1st September 2011, promoted
1095 runoff coefficients ~~for the Ribeirão dos Covões stream~~ of only 5% and 2% respectively
1096 ~~and. These rainfall events resulted in~~ peak ~~stream~~flows of only 0.041 mm h⁻¹ and 0.036 mm
1097 h⁻¹, ~~compared associated~~ with maximum 5-minute rainfall intensities of 2.4 mm h⁻¹ and 9.6
1098 mm h⁻¹ respectively. Thus, hydrophobicity over the catchment does not translate into
1099 catchment-scale overland flow, presumably due to infiltration into sinks ~~and interception~~
1100 downslope. In wet conditions, however, enhanced soil moisture levels seem to increase
1101 flow connectivity over the catchment. Thus rainstorms of 2.8 mm and ~~1415.04~~ mm
1102 registered on 11th February and 28th March 2011, led to 10% and 9% ~~storm~~ runoff
1103 coefficients and peak flows of 0.079 and 0.370 mm h⁻¹, compared with maximum rainfall
1104 intensities of 9.6 mm h⁻¹ in both cases. Although lag times from peak rainfall to peak
1105 streamflow are short, ranging between 25 and 35 minutes, and probably a direct result of
1106 urban surface runoff and the urban drainage system, the overriding feature is the small size
1107 of the storm runoff coefficients both ~~in~~ during dry and wet times of the year, which shows
1108 how little of the rain falling on the peri-urban mosaic actually reaches the stream network.
1109 This may reflect in part ~~of~~ the ridge location of much of the urban expansion to date and in

1110 part a rather high proportion of infiltration into urban soil within the urban units and
1111 adjacent landscape units.

1112 The short lag times, between rainfall and streamflow peaks in urban areas, however, mean
1113 that future urban consolidation and the construction of new urban cores, already proposed,
1114 must be planned carefully in order to minimize urban flood hazard~~however, mean that~~
1115 ~~future urban consolidation and the construction of new urban cores, already projected, must~~
1116 ~~be planned carefully in order to minimize urban flood hazard~~. From the hydrological point
1117 of view, instead of extending the existing urban cores, it would be better to establish new
1118 dispersed urban cores far from the stream network. The maintenance of a patchy mosaic of
1119 dispersed landscape units would reduce overland flow and river flood peak responses.

1120

1121 56 **Conclusions**

1122 The peri-urban *Ribeira dos Covões* catchment is covered by soils of relatively low matrix
1123 infiltration capacity, ~~but and~~ of greater permeability on sandstone than limestone, due to the
1124 ~~latter's~~ marly nature of the latter. ~~The d~~ Different landscape units, associated with different
1125 land-uses and lithologies, display varying responses of soil hydrological properties to
1126 season and to antecedent rainfall with complex consequences for spatial patterns of
1127 overland flow and its flow connectivity. The main findings are:

- 1128 1) In dry conditions, severe hydrophobicity in ~~eucalyptus~~eucalypt and pine (but not
1129 oak) woodland and limestone-agricultural areas (abandoned fields) considerably
1130 reduces soil matrix infiltration capacity. In contrast, ~~urban and~~ agricultural-
1131 sandstone soils (mainly covered by olives, pasture and gardens) and urban soils

Formatted: Space After: 2.4 line

1132 remain mostly hydrophilic, and have relatively high infiltration capacities (~~median~~
1133 ~~values of 3 mm h⁻¹~~). Under wet conditions, hydrophobicity in woodland and
1134 agricultural ~~limestone~~ areas breaks down and infiltration capacity increases,
1135 reaching 6 mm h⁻¹. In contrast, on urban and agricultural ~~sandstone~~ sites, a rise in
1136 soil moisture ~~rise~~ leads to a decline in infiltration capacity ~~decline~~, with soil
1137 saturation occurring in areas of shallow soils and high water tables on hillslopes, in
1138 topographic lows and in valley bottoms.

1139 2) Temporal variability of soil hydrological properties indicates that, in dry conditions,
1140 hydrophobicity-related infiltration-excess overland flow may be generated in
1141 woodland and agricultural-limestone areas, while in wet conditions ~~saturation-~~
1142 ~~excess~~saturation is likely in some locations on urban and agricultural soils.
1143 Nevertheless, soil property heterogeneity and the distinct temporal pattern of
1144 infiltration capacity indicate that much overland flow must be infiltrating before
1145 reaching the stream network in patches of unsaturated soil of relatively high
1146 permeability, either within the same landscape unit or on adjacent landscape units.

1147 3) Despite the generally low soil matrix infiltration capacity across the catchment,
1148 macropores, vegetation, ~~and litter, as well as~~ and surface roughness, play important
1149 roles in surface water retention and facilitating infiltration. Nevertheless, these
1150 processes are influenced by the different landscape units, which provide different
1151 temporal overland flow sinks. Because of this, a patchy mosaic comprising
1152 fragmented and dispersed land-uses, and the tendency for much of recent

1153 urbanization to have occurred along ridges, have to date led to relatively low flow
1154 connectivity over hillslopes, thereby attenuating river discharge peaks.

1155 Understanding how the spatial and temporal variability in overland flow generation and
1156 infiltration affect flow connectivity in a catchment with varied land-use, geology and soils
1157 is vital for predicting flood hazards. Landscape managers and urban planners should
1158 employ a mosaic of different land-uses, where impermeable surfaces are joined
1159 hydrologically to infiltration-promoting “green” areas, in order to prevent or reduce water
1160 excess downstream flooding. There need to be informed decisions about the precise spatial
1161 arrangement of different land-uses.

1162

1163 67 **Acknowledgements**

1164 This study was supported by PhD scholarship SFRH/BD/64493/2009 of the Portuguese
1165 Science and Technology Foundation (FCT), under QREN – POPH – 4.1 Advanced
1166 Training Typology, co-funding by European Social Fund and MEC national funds, and
1167 FRURB project “Managing Flood Risk in Urban areas in a global change context”
1168 (PTDC/AUR-URB/123089/2010) founded by FCT. The authors would like to thank the
1169 Soil and Fertility laboratory of ESAC. We are grateful to Tanya Esteves for ArcGIS
1170 support, and to Daniel Soares and Célia Bento for occasional fieldwork assistance.

1171

1172 78 **References**

1173 | [Álvarez-Mozos, J., Verhoest, N.E.C., Larrañaga, A., Casali, J., González-Audícana, M.,](#)
1174 | [2009. Influence of Surface Roughness Spatial Variability and Temporal Dynamics on the](#)
1175 | [Retrieval of Soil Moisture from SAR Observations. Sensors 9\(1\), 463-489.](#)

1176 | Aryal, S.K., O., Loughlin, E.M., Mein, R.G. A., 2005. Similarity approach to determine
1177 | response times to steady-state saturation in landscapes. *Adv. Water Resour.* 28, 99-115.

1178 | Appels, W.M., Bogaart, P.W., van der Zee, S.E.A.T.M., 2011. Influence of spatial
1179 | variations of microtopography and infiltration on surface runoff and field scale hydrological
1180 | connectivity. *Adv. Water Resour.* 34, 303–313.

1181 | Berglund, K., Persson, L., 1996. Water repellence of cultivated organic soils. *Acta*
1182 | *Agriculturae Sacandinavica Section B Soil and Plant Science* 46, 145-152.

1183 | Borselli, L., Cassi, P., Torri, D., 2008. Prolegomena to sediment and flow connectivity in
1184 | the landscape: A GIS and field numerical assessment. *Catena.* 75, 268–277.

1185 | Boyd, M. J., Bufill, M. C., Dnee, R. M., 1993. Pervious and impervious runoff in urban
1186 | catchments. *Hydrological Sciences.* 38, 463-478.

1187 | Bracken, L.J., Croke, J., 2007. The concept of hydrological connectivity and its
1188 | contribution to understanding runoff-dominated geomorphic systems. *Hydrol. Process.* 21,
1189 | 1749–1763.

1190 | Bull, L.J., Kirkby, M.J., Shannon, J., Dunsford, H.D., 2003. Predicting hydrologically
1191 | similar surfaces (HYSS) in semi-arid environments. *Adv. Env. Monit. Mod.* 2, 1–13.

1192 | [Buttle, J.M., Dillon, P.J., Eerkes, G.R., 2004. Hydrologic coupling of slopes, riparian zones](#)
1193 | [and streams: an example from the Canadian Shield. J. Hydrol. 287, 161–177.](#)

1194 Cammeraat, L.H., 2002. A review of two strongly contrasting geomorphological systems
1195 within the context of scale. *Earth Surf. Proc. Landf.* 27, 1201–1222.

1196 Carrick, S., Buchan, G., Almond, P., Smith, N., 2011. Atypical early-time infiltration into a
1197 structured soil near field capacity: The dynamic interplay between sorptivity,
1198 hydrophobicity, and air encapsulation. *Geoderma*. 160, 579-589.

1199 ~~[Castillo, V.M., Gómez Plaza, A., Martínez Mena, M., 2003. The role of antecedent soil](#)~~
1200 ~~[water content in the runoff response of semiarid catchments: a simulation approach. *J.*](#)~~
1201 ~~[Hydrol.](#) 284, 114–130.~~

1202 Cerdà, A., 1997. Seasonal changes of the infiltration rates in a Mediterranean scrubland on
1203 limestone. *J. Hydrol.* 198, 209–225.

1204 Celik, I., Gunal, H., Budak, M., Akpinar, C., 2010. Effects of long-term organic and
1205 mineral fertilizers on bulk density and penetration resistance in semi-arid Mediterranean
1206 soil conditions. *Geoderma* 160, 236–243.

1207 ~~[Costa, J.B., 1999. Caracterização e constituição do solo, sixth edition. Fundação Calouste](#)~~
1208 ~~[Gulbenkian, Lisboa.](#)~~

1209 Costa, M.H., Botta, A., Cardille, J.A., 2003. Effects of large-scale changes in land cover on
1210 the discharge of the Tocantins River, Southeastern Amazonia. *J. Hydrol.* 283, 206–217.

1211 Dane, J.H., Topp, C., 2002. *Methods of Soil Analysis, Part 4 – Physical Methods*. Soil
1212 Science Society of America Book Series, Wisconsin, USA.

- 1213 | ~~Darboux, F., Davy, P., Gascuel Odoux, C., Huang, C., 2001. Evolution of soil surface~~
1214 | ~~roughness and flowpath connectivity in overland flow experiments. Catena 46(2-3), 125-~~
1215 | ~~39.~~
- 1216 DeBano, L.F., 1991. The effect of fire on soil properties. US Department of Agriculture,
1217 Forest Service General Technical Report. INT-280.
- 1218 DeBano, L.F., 2000. Water repellency in soils: a historical overview. J. Hydrol. 231-232, 4-
1219 32.
- 1220 | Decagon, 2007. Mini-infiltrometer manual, Version 4. Decagon Devices Inc., Pullman,
1221 | WA.
- 1222 Dekker, L.W., Ritsema, C.J., 1994. How water moves in a water repellent sandy soil. I.
1223 Potential and actual water repellency. Water Resour. Res. 30, 2507–2517.
- 1224 Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., 1998. Spatial variability of soil
1225 | hydrophobicity in fire-prone ~~eucalypt~~eucalypt and pine forests, Portugal. Soil Sci. 163,
1226 | 313–324.
- 1227 Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., 2000. Soil water repellency, its causes,
1228 characteristics and hydro-geomorphological significance. Earth-Sci. Rev. 51, 33-65.
- 1229 Doerr, S.H., Thomas, A.D., 2000. The role of soil moisture in controlling water repellency,
1230 new evidence from forest soils in Portugal. J. Hydrol. 231-232, 134–147.
- 1231 Dornauf, C., Burghardt, W., 2000. The effects of biopores on permeability and storm
1232 infiltration – case study of the construction of a school. In, Burghardt, W., Dornayf, C.

1233 (eds) First International conference on soils of urban, industrial, traffic and mining areas.
1234 University of Essens, Essen, pp. 459-464.

1235 [Duiker, S.W., 2011. Crop residue survey 2010. Field Crop News 11, 5-](#)
1236 Easton, Z.M., Gérard-Marchant, P., Walter, M.T., Petrovic, A.M., Steenhuis, T.S., 2007.
1237 Hydrologic assessment of an urban variable source watershed in the Northeast United
1238 States. Water Resour. Res. 43, W03413.

1239 ~~[Easton, Z.M., Petrovic, A.M., 2008. Determining nitrogen loading rates based on land use](#)~~
1240 ~~[in urban watershed. In Nett, M.T., Carrol, M.J., Horgan, B.P., Petrovic, A.M. \(eds\) The fate](#)~~
1241 ~~[of nutrients and pesticides in the urban environment. American Chemical Society,](#)~~
1242 ~~[Washington DC, pp. 19-25.](#)~~

1243 Fernández, J.M., Ceballos, A., 2003. Temporal stability of soil moisture in a large-field
1244 experiment in Spain. Soil Sci. Soc. Am. J. 67, 1647–1656.

1245 Ferreira, C.S.S., Soares, D., Ferreira, A.J.D., Coelho, C.O.A., Steenhuis, T.S., Keizer, J.J.,
1246 Walsh, R.P.D., 2012a. The role of forest in runoff generation in a suburban catchment.
1247 European Geoscience Union General Assembly, 22-27 April, Vienna, Austria. 14, 1014.

1248 ~~[Ferreira, C.S.S., Steenhuis, T.S., Soares, D., Ferreira, A.J.D., Walsh, R.P.D., Coelho,](#)~~
1249 ~~[C.O.A., de Lima, J.L.M., 2012b. The role of spatiotemporal variability of the hydrological](#)~~
1250 ~~[processes on flow connectivity in an urbanizing watershed. 14th Biennial Conference ERB](#)~~
1251 ~~[2012—Euromediterranean Network of Experimental and Representative Basins Conference](#)~~
1252 ~~[on Studies of Hydrological Processes in Research Basins, Current Challenges and](#)~~
1253 ~~[Prospects, 17-20 September, St. Petersburg.](#)~~

1254 Ferreira, C.S.S., Ferreira, A.J.D., Pato, R.L., Magalhães, M.C., Coelho, C.O., Santos, C.,
1255 ~~[2012e2012b](#)~~. Rainfall-runoff-erosion relationships study for different land-uses, in a sub-
1256 urban area. Z. Geomorphol. 56(3), 5-20.

1257 ~~[Ferreira, C.S.S., Steenhuis, T.S., Walsh, R.P.D., Soares, D., Ferreira, A.J.D., Coelho,](#)~~
1258 ~~[C.O.A., 2013. Land use change impacts on hydrologic soil properties and implications for](#)~~
1259 ~~[overland flow in a periurban Mediterranean catchment. European Geoscience Union](#)~~
1260 ~~[General Assembly, 07-12 April, Vienna, Austria. 15, 972.](#)~~

1261 Ferreira, A.J.D., 1996. Processos hidrológicos e hidroquímicos em povoamentos de
1262 ~~[EucalyptusEucalypt](#)~~ *globulus Labill.* e *Pinus pinaster Aiton*. PhDThesis, Departamento de
1263 Ambiente e Ordenamento, Universidade de Aveiro, Portugal.

1264 ~~[Gentine, P., Troy, T.J., Lintner, B.R., Findell, K.L., 2012. Scaling in Surface Hydrology:](#)~~
1265 ~~[Progress and Challenges. J. Contemp. Water Res. & Educ. 147, 28-40.](#)~~

1266 Glenn, N.F., Finley, C.D., 2010. Fire and vegetation type effects on soil hydrophobicity and
1267 infiltration in the sagebrush-steppe: I. Field analysis. J. Arid Environ. 74, 653-659.

1268 Hardie, M.A., Cotching, W. E., Doyle, R.B., Holz, G., Lisson, S., Mattern, K., 2011. Effect
1269 of antecedent soil moisture on preferential flow in a texture-contrast soil. J. Hydrol. 398,
1270 191–201.

1271 Hardie, M.A., Doyle, R.B., Cotching, W. E., Mattern, K., Lisson, S., 2012. Influence of
1272 antecedent soil moisture on hydraulic conductivity in a series of texture-contrast soils.
1273 Hydrol. Process. 26, 3079–3091.

- 1274 Holden, J., 2008. An Introduction to Physical Geography and the Environment. 2nd Edition,
1275 ISBN-10, 0131753045.
- 1276 Hopp, L., McDonnell, J.J., 2009. Connectivity at the hillslope scale, identifying interactions
1277 between storm size, bedrock permeability, slope angle and soil depth. *J. Hydrol.* 376, 378–
1278 391.
- 1279 INMG, Instituto Nacional de Meteorologia e Geofísica, 1941-2000. Anuário climatológico
1280 de Portugal. I Parte, Continente, Açores e Madeira – Observações de superfície. Lisboa.
- 1281 Jordán, A., Martínez-Zavala, L., Bellinfante, N., 2008. Heterogeneity in soil hydrological
1282 response from different land cover types in southern Spain. *Catena* 74, 137–143.
- 1283 ~~Kargas, G., Kerkides, P., Poulouvasilis, A., 2012. Infiltration of rain water in semi arid~~
1284 ~~areas under three land surface treatments. *Soil Till. Res.* 120, 15–24.~~
- 1285 Keizer, J.J., Doerr, S.H., Malvar, M.C., Ferreira, A.J.D., Pereira, V.M.F.G., 2008.
1286 Temporal and spatial variations in topsoil water repellency throughout a crop-rotation cycle
1287 on sandy soil in north-central Portugal. *Hydrol. Process.* 21, 2317–2324.
- 1288 Kirkby, M., Bracken, L., Reaney, S., 2002. The influence of land-use, soils and topography
1289 on the delivery of hillslope runoff to channels in SE Spain. *Earth Surf. Proc. Land.* 27,
1290 1459–1473.
- 1291 Konrad, C.P., Booth, D.B., 2005. Hydrologic changes in urban streams and their ecological
1292 significance. In, *Effects of urbanization on stream ecosystems.* (Eds. L.R. Brown, R.H.
1293 Gray, R.M. Hughes & M.R. Meador), American Fisheries Society Symposium. 47, 157-
1294 177.

- 1295 Latron, J., Gallart, F., 2007. Seasonal dynamics of runoff-contributing areas in a small
1296 mediterranean research catchment (Vallcebre, Eastern Pyrenees). *J. Hydrol.* 335, 194– 206.
- 1297 ~~[Leighton-Boyce, G., 2002. Spatio-temporal dynamics and hydrogeomorphic implications of](#)~~
1298 ~~[soil-water repellency within Eucalyptus Eucalypt forests in north-central Portugal.](#)~~
1299 ~~[Unpublished Ph.D. thesis, University of Wales Swansea. Leighton-Boyce, G., Shakesby,](#)~~
1300 ~~[R.A., Doerr, S.H., Walsh, R.P.D., Ferreira, A.J.D., Boulet, A.K., Coelho C.O.A., 2005.](#)~~
1301 ~~[Temporal dynamics of water repellency and soil moisture in eucalypt plantations, Portugal.](#)~~
1302 ~~[Aust. J. Soil Res. 43, 269-280.](#)~~
- 1303
- 1304 Li, X.Y., González, A., Solé-Benet, A., 2005. Laboratory methods for the estimation of
1305 infiltration capacity of soil crusts in the Tabernas Desert badlands. *Catena.* 60, 255–266.
- 1306 ~~[Lopez-Vicente, M., Navas, A., Machin, J., 2009. The effect of physiographic conditions on](#)~~
1307 ~~[the spatial variation of seasonal topsoil moisture in Mediterranean soils. Australian J. Soil](#)~~
1308 ~~[Res. 47, 498–507.](#)~~
- 1309 López-Vicente, M., Poesen, J., Navas, A., Gaspar, L., 2013. Predicting runoff and sediment
1310 connectivity and soil erosion by water for different land-use scenarios in the Spanish Pre-
1311 Pyrenees. *Catena.* 102, 62–73.
- 1312 Mallick, K., Bhattacharya, B.K., Patel, N.K., 2009. Estimating volumetric surface moisture
1313 content for cropped soils using a soil wetness index based on surface temperature and
1314 NDVI. *Agr. Forest Meteorol.* 149, 1327–1342.

- 1315 Martínez-Zavala, L., Jordán-López, A., 2009. Influence of different plant species on water
1316 repellency in Mediterranean heathland soils. *Catena*. 76, 215–223.
- 1317 McKissock, I., Walker, E.L., Gilkes, R.J., Carter, D.J., 2000. The influence of clay type on
1318 reduction of water repellency by applied clays, a review of some West Australian work. *J.*
1319 *Hydrol.* 231, 323–332.
- 1320 Mouri, G., Kanae, S., Oki, T., 2011. Long-term changes in flood event patterns due to
1321 changes in hydrological distribution parameters in a rural–urban catchment, Shikoku,
1322 Japan. *Atmos. Res.* 101, 164–177.
- 1323 | Neris, J., Tejedor, M., Rodríguez, M., Fuentes, J., Jiménez, C., 2013. Effect of
1324 forest floor characteristics on water repellency, infiltration, runoff and soil loss in Andisols
1325 of Tenerife (Canary Islands, Spain). *Catena* 108, 50-57.
- 1326 Nunes, A.N., Almeida, A.C., Coelho, C.O.A., 2011. Impacts of land-use and cover type on
1327 runoff and soil erosion in a marginal area of Portugal. *Appl. Geog.* 31, 687-699.
- 1328 | Nyman, P., Sheridan, G.J., Smith, H.G., Lane, P.N.J., 2014. Modeling the effects of
1329 surface storage, macropore flow and water repellency on infiltration after wildfire. *J.*
1330 *Hydrol.* (in press).
- 1331 Orfánus, T., Dlapa, P., Fodor, N., Rajkai, K., Sándor, R., Nováková, K., 2014. How severe
1332 and subcritical water repellency determines the seasonal infiltration in natural and
1333 cultivated sandy soils. *Soil & Till. Res.* 135, 49-59.

- 1334 | [Pelleng, J., Lalma, J., Boulet, G., Saulnier, G. M., Wooldridge, S., Kerr, Y., Chehbouni, A.,](#)
1335 | [2003. A disaggregation scheme for soil moisture based on topography and soil depth. J.](#)
1336 | [Hydrol. 276, 112–127.](#)
- 1337 | Rahardjo, H., Indrawan, I.G.B., Leong, E.C., Yong, W.K., 2008. Effects of coarse-grained
1338 | material on hydraulic properties and shear strength of top soil. Eng. Geol. 101, 165–173.
- 1339 | [Ritsema, C.J., Dekker, L.W., Heijs, A.W.J., 1997. Three dimensional fingered flow](#)
1340 | [patterns in a water repellent sandy field soil. Soil Sci. 162, 79–90.](#)
- 1341 | Rodríguez-Caballero, E., Cantón, Y., Chamizo, S., Afana, A., Solé-Benet, A., 2012. Effects
1342 | of biological soil crusts on surface roughness and implications for runoff and erosion.
1343 | Geomorphology 145-146, 81–89.
- 1344 | Santos J.M., Verheijen F.G.A., Tavares Wahren F., Wahren A., Feger K.-H., Bernard-
1345 | Jannin L., Rial-Rivas M.E., Keizer J.J., Nunes J.P. In press. Soil water repellency dynamics
1346 | in pine and eucalypt plantations in Portugal - a high-resolution time series. Land
1347 | Degradation and Development, in press. DOI: 10.1002/ldr.2251.
- 1348 | Silva, A.P., Kay, B.D., Perfect, E., 1997. Management versus inherent soil properties
1349 | effects on bulk density and relative compaction. Soil Till. Res. 44, 81-93.
- 1350 | [Soil Survey Division Staff, 1993. Soil survey manual. Soil Conservation Service. U.S.](#)
1351 | [Department of Agriculture Handbook 18.](#)
- 1352 | Soto, B., Basanta, R., Benito, E., Perez, R., Diaz-Fierros, F., 1994. Runoff and erosion from
1353 | burnet soils in northwest Spain. In: Sala M., Rubio J.L. (eds) Soil erosion as a Consequence
1354 | of Forest Fires. Geoforma Ediciones, Logroño, pp.91-98.

1355 Tavares, A.O., Pato, R.L., Magalhães, M.C., 2012. Spatial and temporal land-use change
1356 and occupation over the last half century in a peri-urban area. *Appl. Geog.* 34, 432-444.

1357 [Uchida, T., Kosugi, K., Miizuyama, T., 1999. Runoff characteristics of pipeflow and effects](#)
1358 [of pipeflow on rainfall-runoff phenomena in a mountainous watershed. *J. Hydrol.* 222\(1-4\),](#)
1359 [18-36.](#)

1360 Urbanek, E., Shakesby, R.A., 2009. The impact of stone content on water flow in water-
1361 repellent sand. *Eur. J. Soil Sci.* 60, 412-419.

1362 Valente, F., David, J.S., and Gash, J.H.C., 1997. Modelling interception loss for two sparse
1363 eucalypt and pine forests in central Portugal using reformulated Rutter and Gash analytical
1364 models. *J. Hydrol.* 190, 141–162.

1365 [van Schaik, N.L.M.B., Schnabel, S., Jetten, V.G., 2008. The influence of preferential flow](#)
1366 [on hillslope hydrology in a semi-arid watershed \(in the Spanish Dehesas\). *Hydrol. Process.*](#)
1367 [22\(18\), 3844-3855.](#)

1368 Varela, M.E., Benito, E., de Blas, E., 2005. Impact of wildfires on surface water
1369 repellency in soils of northwest Spain. *Hydrol. Process.* 19, 3649–3657.

1370 Walter, M.T., Walter, M.F., Brooks, E.S., Steenhuis, T.S., Boll, J., Weiler, K.R., 2000.
1371 Hydrologically sensitive areas, variable source area hydrology implications for water
1372 quality risk assessment. *J. Soil Water Conserv.* 3, 277-284.

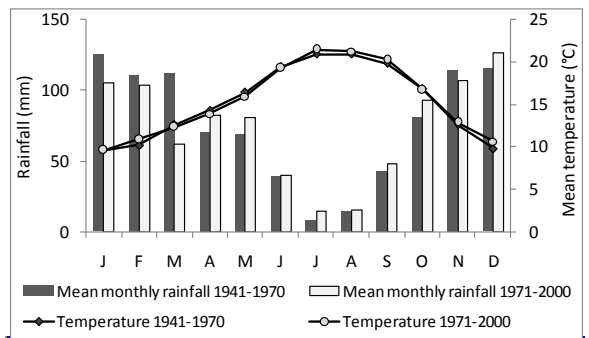
1373 [Wang, Z., Wua, Q.J., Wua, L., Ritsema, C.J., Dekker, L.W., Feyen, J., 2000. Effects of soil](#)
1374 [water repellency on infiltration rate and flow instability. *J. Hydrol.* 231–232, 265–276.](#)

- 1375 Wilson, D.J., Western, A.W., Grayson, R.B., 2005. A terrain and data-based method for
1376 generating the spatial distribution of soil moisture. *Adv. Water Resour.* 28, 43–54
- 1377 Yang, J.L., Zhang, G.L., 2011. Water infiltration in urban soils and its effects on the
1378 quantity and quality of runoff. *J. Soils Sediment.* 11, 751–761.
- 1379 Yu, X., Duffy, C., Baldwin, D.C., Lin, H., 2014. The role of macropores and multi-
1380 resolution soil survey datasets for distributed surface-subsurface flow modeling. *J. Hydrol.*
1381 in press. Doi, <http://dx.doi.org/10.1016/j.jhydrol.2014.02.055>.
- 1382 Zavala, L., González, F.A., Jordán, A., 2009. Intensity and persistence of water repellency
1383 in relation to vegetation types and soil parameters in Mediterranean SW Spain. *Geoderma*
1384 152, 361–374.
- 1385 Zhang, R., 1997. Determination of soil sorptivity and hydraulic conductivity from the disk
1386 infiltrometer. *Soil Sci. Soc. Am. J.* 61, 1024–1030.

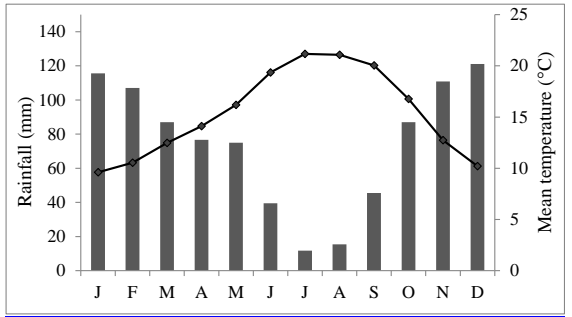
1387

1388 **Figures**

Formatted: Font: Bold



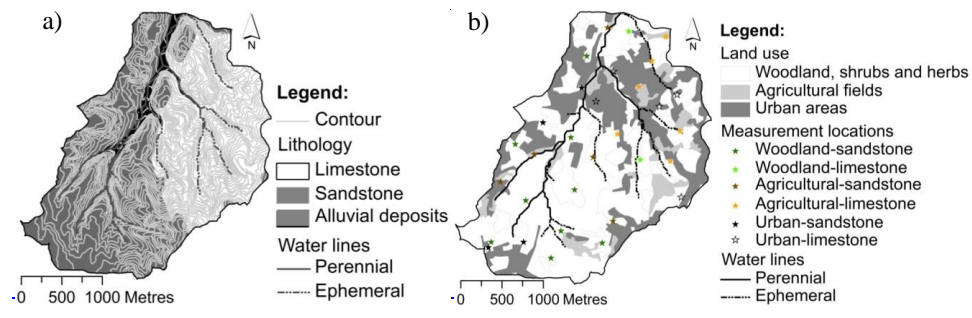
1389



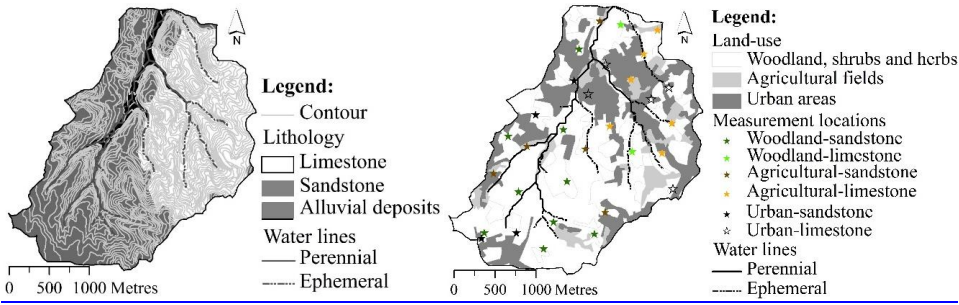
1390

1391 Figure 1 – Average monthly rainfall and temperature at Coimbra (Bencanta weather
1392 station) for the periods 1941-1970 and 1971-2000 (INMG, 1941-2000).

1393

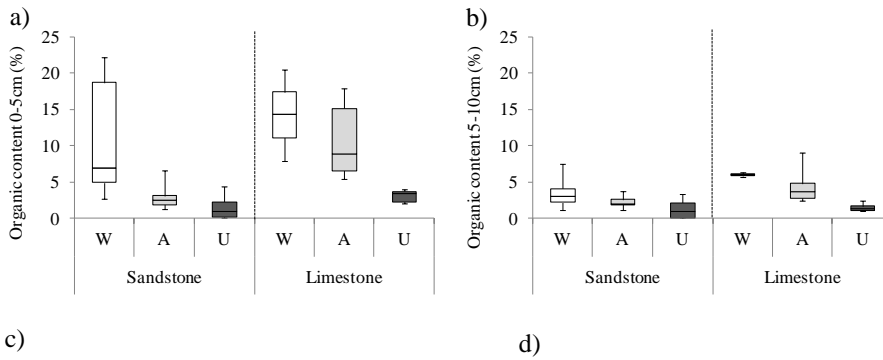


1394



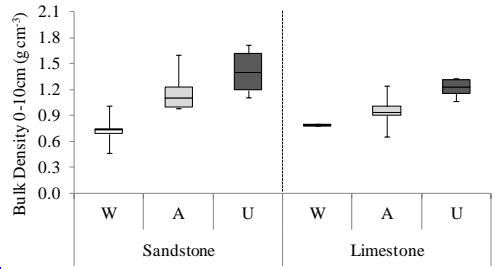
1395
 1396 Figure 2 – Ribeira dos Covões catchment: (a) topography, lithology and streams; (b) land-
 1397 use in 2009 and location of the study sites.

1398

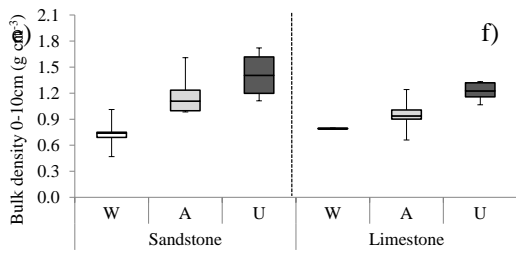


1399

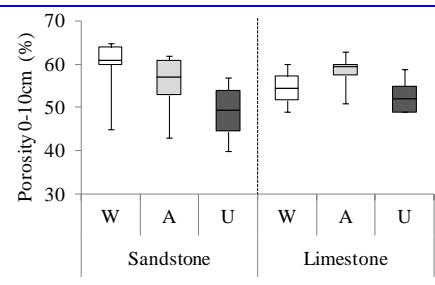
1400

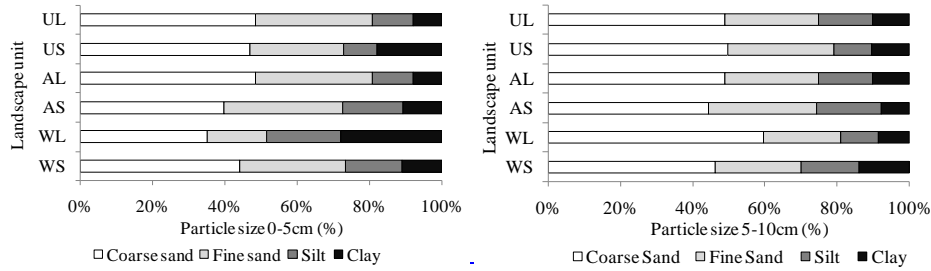


1401

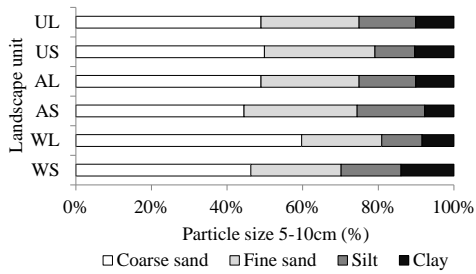


1402





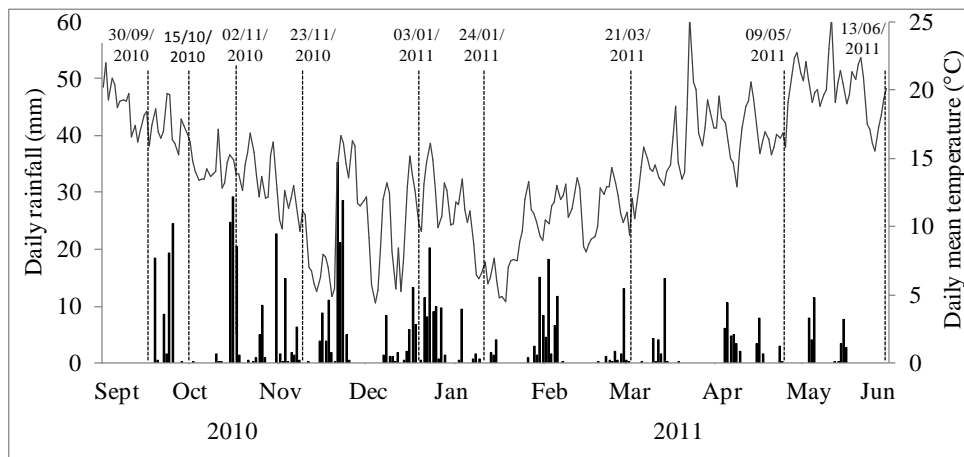
1403



1404

1405 Figure 3 – Soil properties in different landscape units: a) organic matter content at the
 1406 surface (0-5cm) and b) subsurface (5-10cm), c) bulk density (0-10cm), d) porosity (0-
 1407 10cm), e) particle size distribution of surface (0-5cm), and f) subsurface soil (5-10cm) (W:
 1408 woodland, A: agricultural, U: urban, S: sandstone, L: limestone).

1409

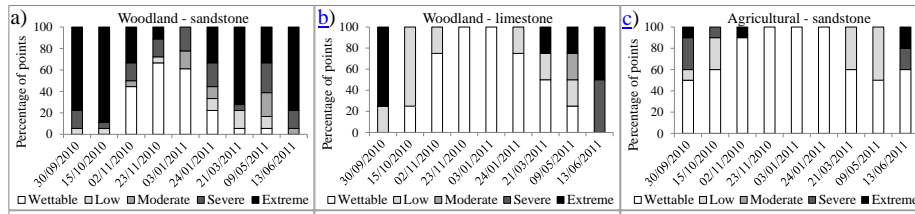


1410

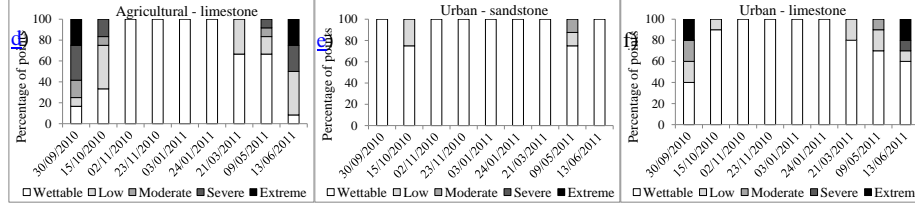
1411 Figure 4 – Daily rainfall and mean daily temperature during the monitoring period
1412 September 2010 – May 2011 with dates of field measurements.

1413

1414



1415



1416

Figure 5 – Temporal variability of surface hydrophobicity for individual landscape units: a)

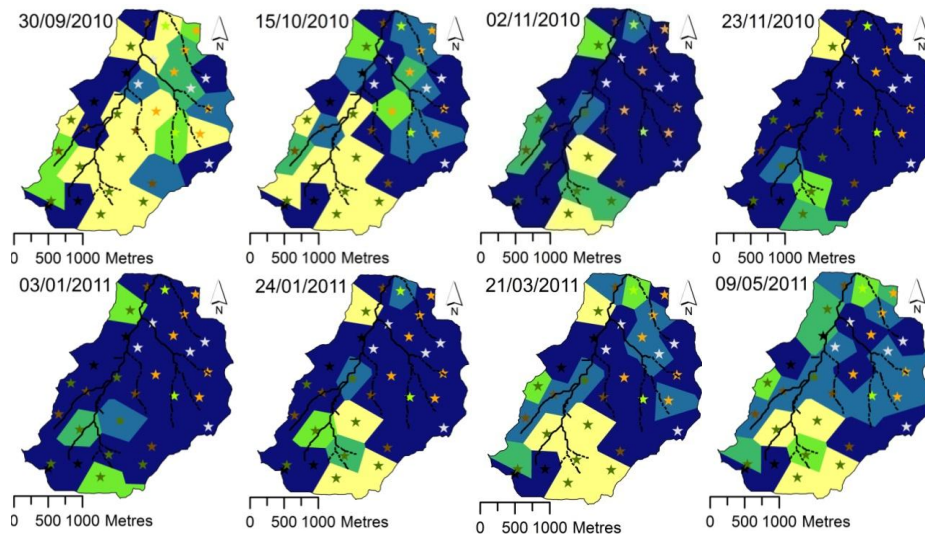
1417

b) woodland-limestone, c) agricultural-sandstone, d) agricultural-

1418

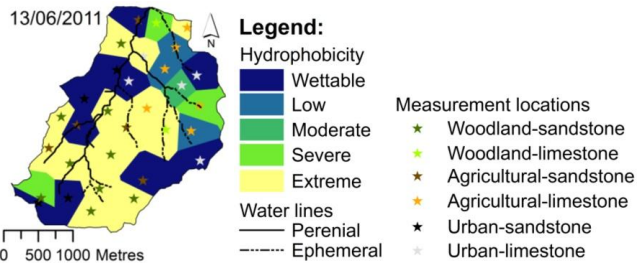
limestone, e) urban-sandstone, f) urban-limestone.

1419



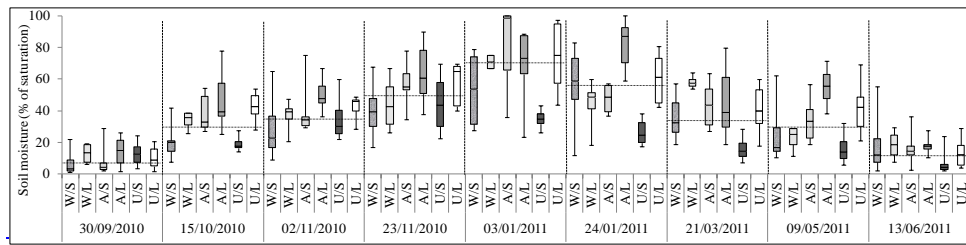
1420

1421

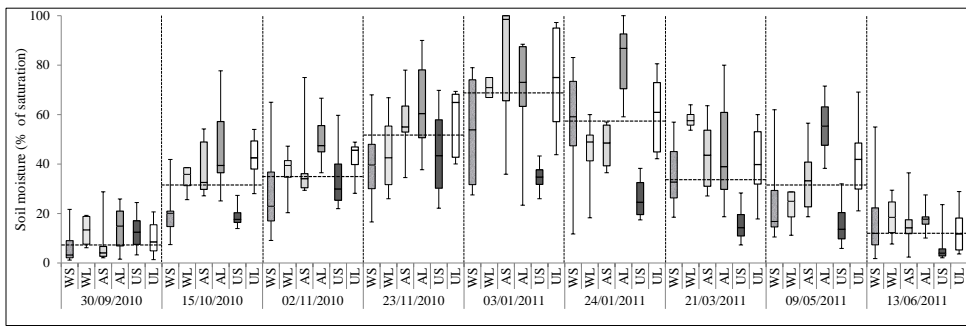


1422

1423 Figure 6 – Spatial variation of median soil hydrophobicity at the measurement dates, based
 1424 on the Thiessen polygon method.

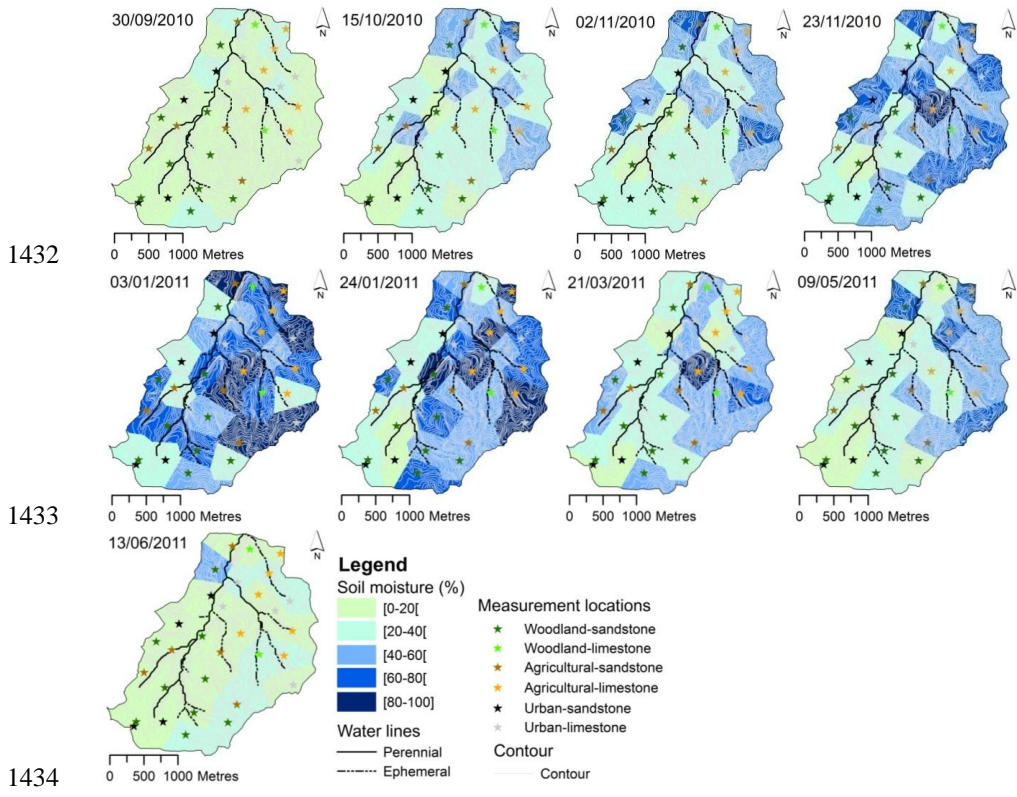


1425
 1426



1427

1428 Figure 7 – Box-plots of soil moisture content for the different landscape units for the study
 1429 period (W: woodland, A: agricultural, U: urban, S: sandstone, L: limestone). Horizontal
 1430 dashed lines represent median soil moistures across the catchment, for the 9 measurement
 1431 dates.



1432

1433

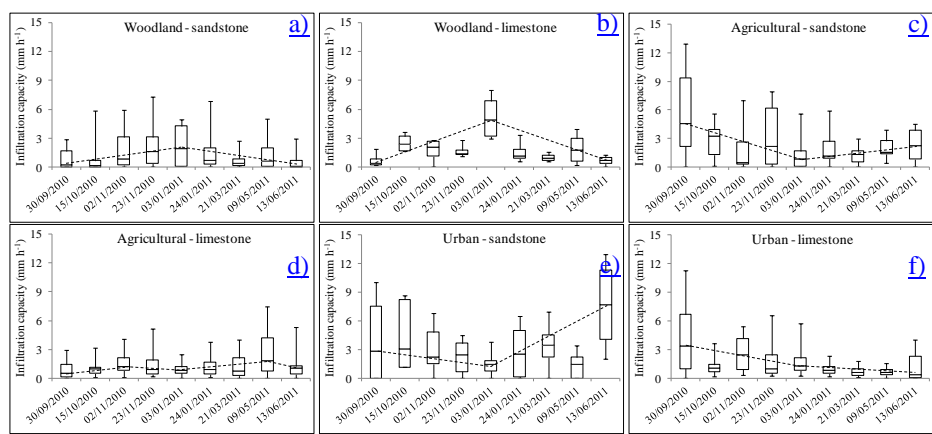
1434

1435 Figure 8 – Spatial distribution in median soil moisture content for each the measurement
 1436 date, using the Thiessen polygon method.

1437

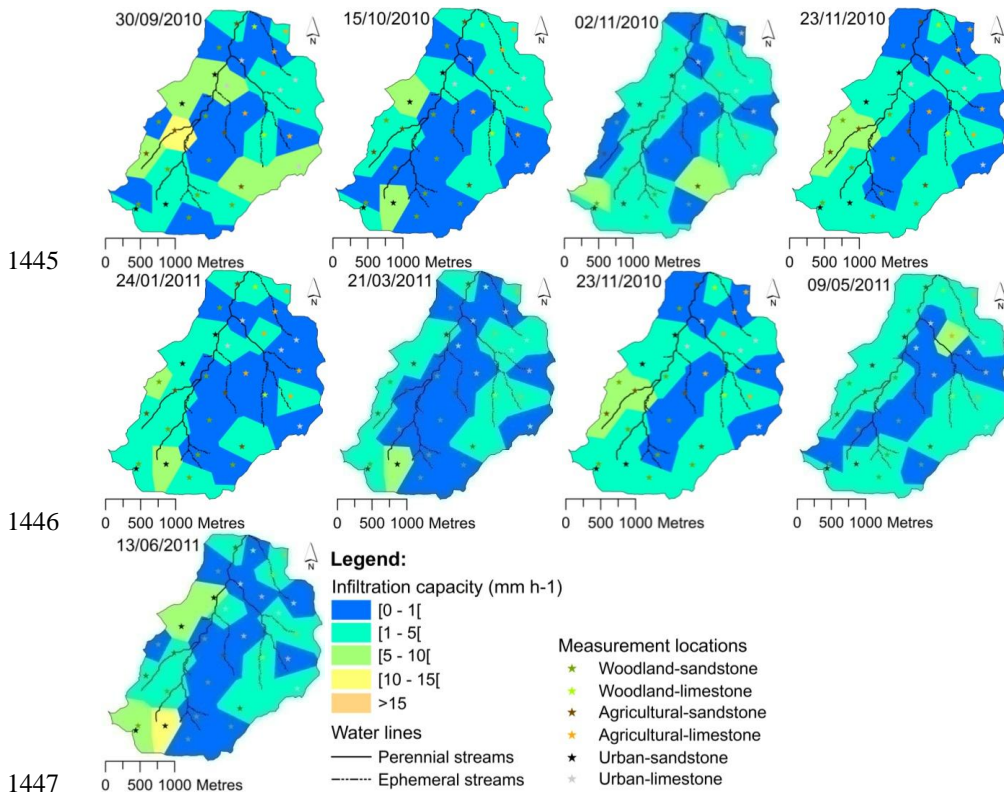
1438

1439



1440 Figure 9 – Box plots of temporal variability of matrix soil infiltration capacity for each
 1441 landscape unit. Dashed lines represent median temporal variability through the whole study
 1442 period: [a\) woodland-sandstone](#), [b\) woodland-limestone](#), [c\) agricultural-sandstone](#), [d\)](#)
 1443 [agricultural-limestone](#), [e\) urban-sandstone](#), [f\) urban-limestone](#).

1444



1449 Figure 10 - Spatial variation in median matrix soil infiltration capacity at each measurement
 1450 dates, [considering Thiessen Polygon method for data distribution](#).

1451

1452

1453

1454 **Tables**

1455 Table 1 – Rainfall and mean temperature in the days prior to measurement dates.

Measurement date	Total rainfall between measurements (mm)	Antecedent rainfall (mm)				Mean temperature during previous 5 days (°C)
		2 days	5 days	10 days	30 days	
30/09/2010	-	0.0	0.0	0.0	5.0	18.9
15/10/2010	72.6	0.0	0.2	53.8	72.6	16.7
02/11/2010	77.2	1.2	75.4	77.2	131.6	14.1
23/11/2010	66.0	0.4	9.6	49.0	141.8	11.4
03/01/2011	161.5	0.5	26	30.2	131.5	12.3
24/01/2011	82.8	0.7	2.6	12.3	112.5	6.9
21/03/2011	97.0	0.2	0.2	15.8	19.8	13.1
09/05/2011	72.328	0.2	3.1	12.5	47.2	16.3
13/06/2011	37.0	0.0	0	0.0	37.0	18.1

1456

1457 Table 2 – Principal Component Analysis results considering only hydrophobicity at
 1458 different depths and soil moisture variables.

Factors	FC 1
Hydrophobicity (0cm)	0.780
Hydrophobicity (2cm)	0.894
Hydrophobicity (5cm)	0.893
Soil moisture (0-5cm)	-0.595
Cumulative variance explained (%)	64.0

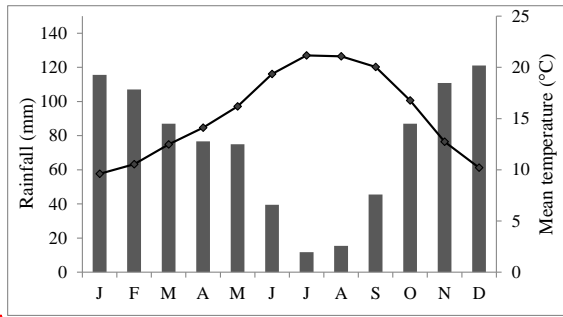
1459

1460 Table 3 - Principal Component Analysis results including hydrophobicity, soil moisture and
 1461 soil properties at different depths.

Factors	FC 1	FC 2	FC 3
Hydrophobicity (0cm)	-0.108	0.772	-0.230
Hydrophobicity (2cm)	-0.297	0.809	-0.214
Hydrophobicity (5cm)	-0.298	0.777	-0.314
Soil moisture (0-5cm)	0.378	-0.342	0.518
Organic matter content (0-5 cm)	0.044	0.622	0.627
Organic matter content (5-10 cm)	0.247	0.580	0.652

Coarse sand (0-5 cm)	-0.831	-0.163	-0.075
Coarse sand (5-10 cm)	-0.907	-0.150	0.169
Silt (0-5 cm)	0.870	0.183	0.006
Silt (5-10 cm)	0.906	0.170	-0.173
Clay (5-10 cm)	0.714	-0.100	-0.454
<hr/>			
Cumulative variance explained (%)	36.3	61.9	76.0
<hr/>			

1462



Formatted: English (U.K.)
 Formatted
 Formatted: English (U.K.)

Figure 1 – Average monthly rainfall and temperature at Coimbra (Bencanta weather station), calculated from data regarding to ~~for~~ the periods 1941-1970 ~~and~~ 1971-2000 (INMG, 1941-2000).

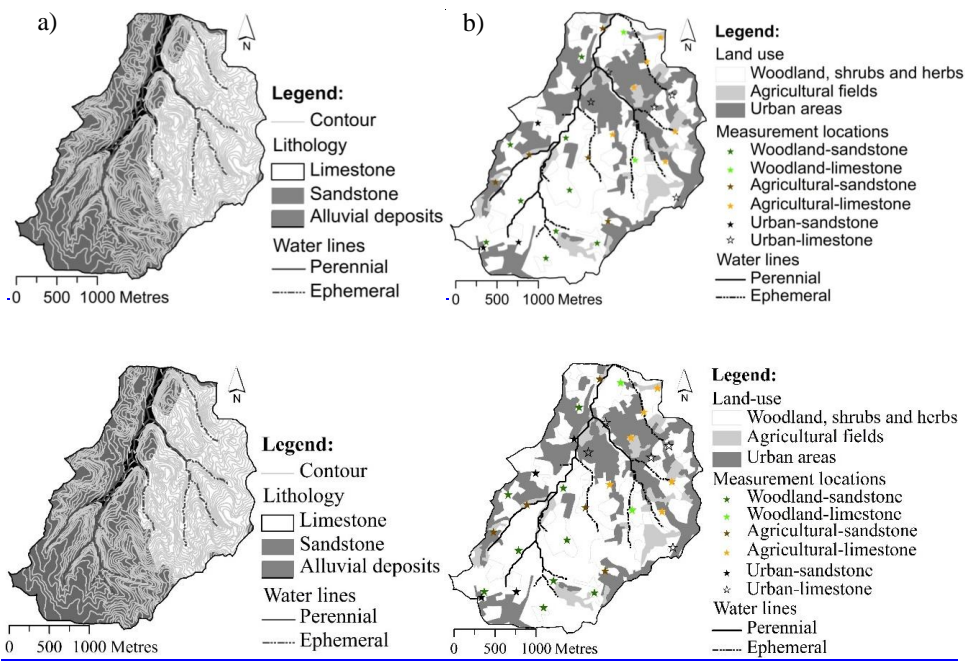
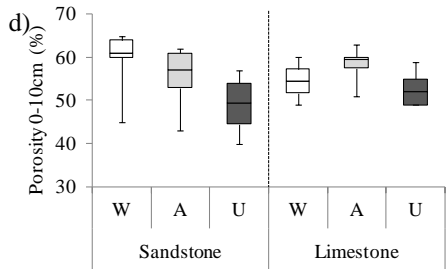
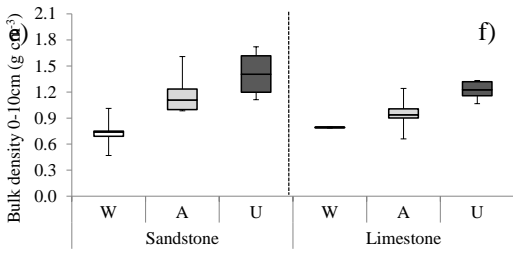
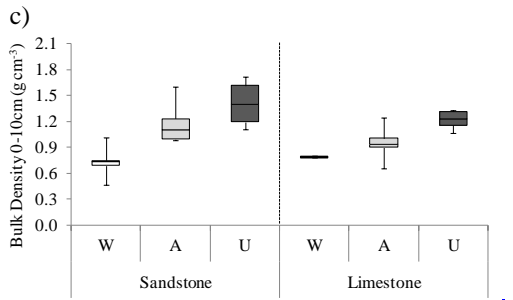
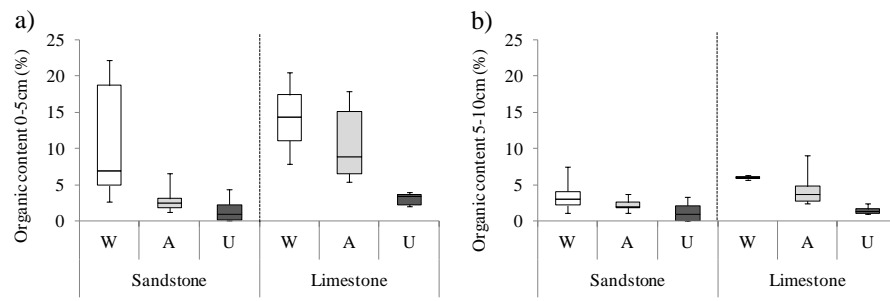


Figure 2 – Ribeira dos Covões catchment: (a) topography, lithology and streams; (b) land-use in 2009 and location of the study sites.



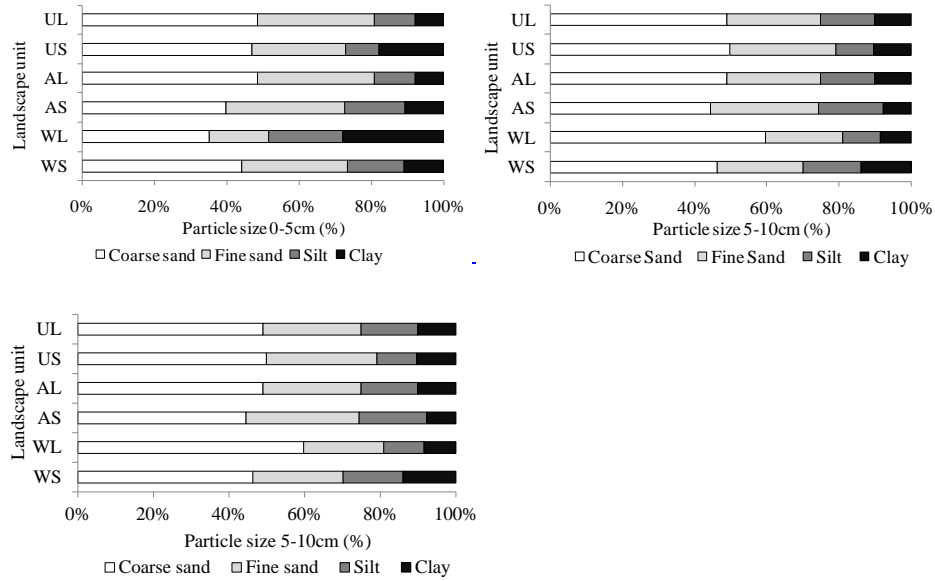
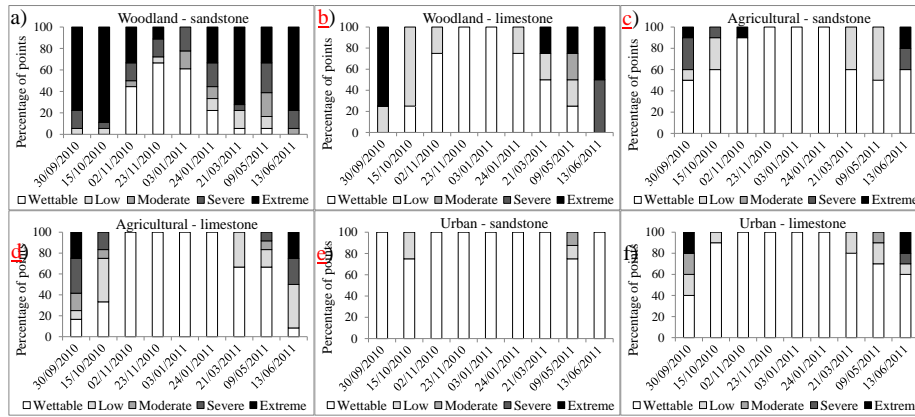


Figure 3 – Soil properties in different landscape units: a) organic matter content at the surface (0-5cm) and b) subsurface (5-10cm), c) bulk density (0-10cm), d) porosity (0-10cm), e) particle size distribution of surface (0-5cm), and f) subsurface soil (5-10cm) (W: woodland, A: agricultural, U: urban, S: sandstone, L: limestone).



Formatted

Formatted: English (U.K.)

Figure 5 – Temporal variability of surface hydrophobicity for individual landscape units: a) woodland-sandstone, b) woodland-limestone, c) agricultural-sandstone, d) agricultural-limestone, e) urban-sandstone, f) urban-limestone.

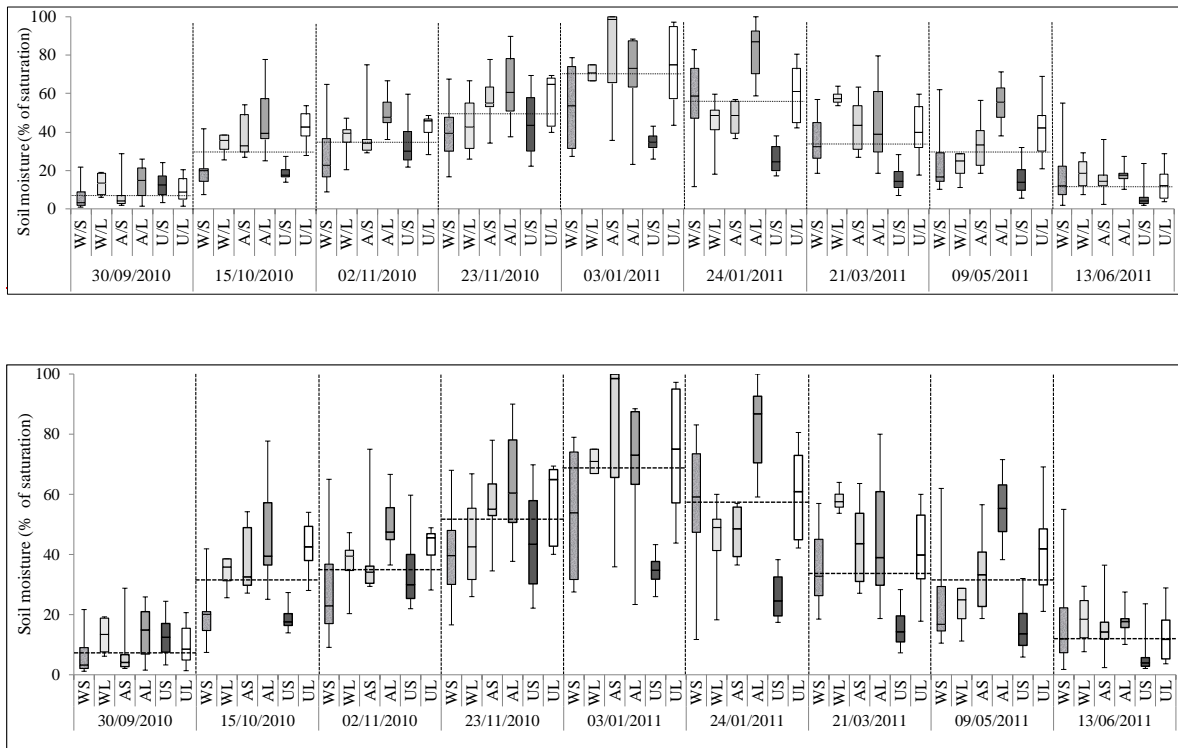


Figure 7 – Box-plots of soil moisture content for the different landscape units for the study period (W: woodland, A: agricultural, U: urban, S: sandstone, L: limestone). Horizontal dashed lines represent median soil moistures across the catchment, for the 9 measurement dates.

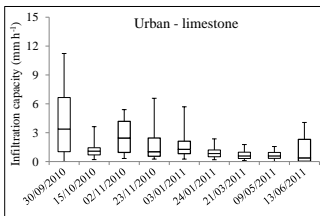
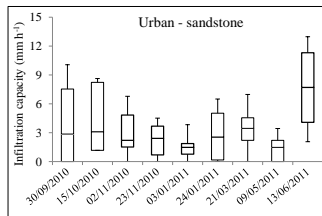
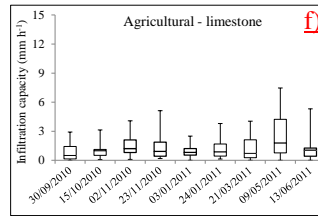
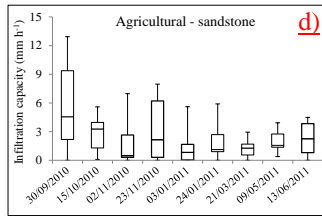
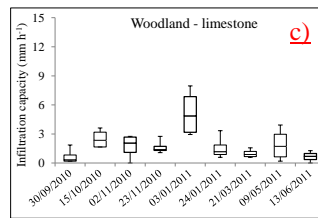
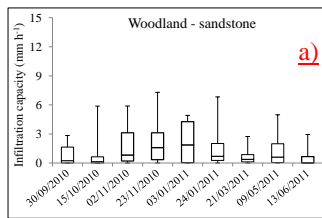
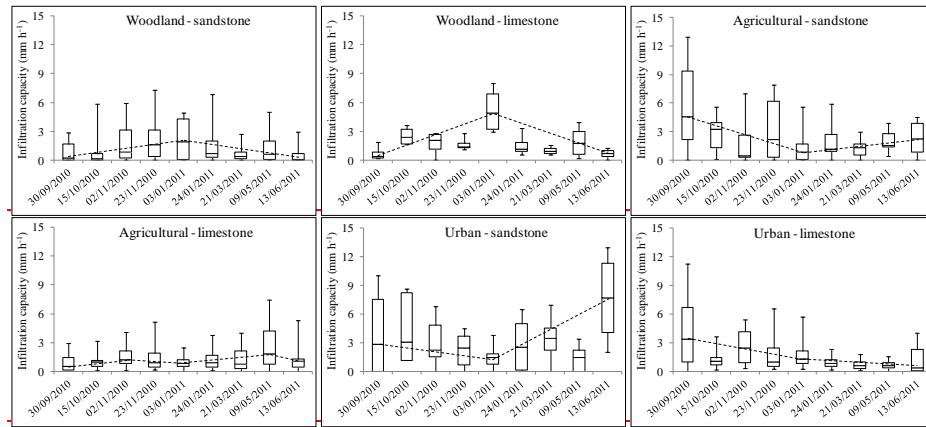


Figure 9 – Box plots of temporal variability of matrix soil infiltration capacity for each landscape unit. **Dashed lines represent median temporal variability through the whole study period** **a)** woodland-sandstone, **b)** woodland-limestone, **c)** agricultural-sandstone, **d)** agricultural-limestone, **e)** urban-sandstone, **f)** urban-limestone.-

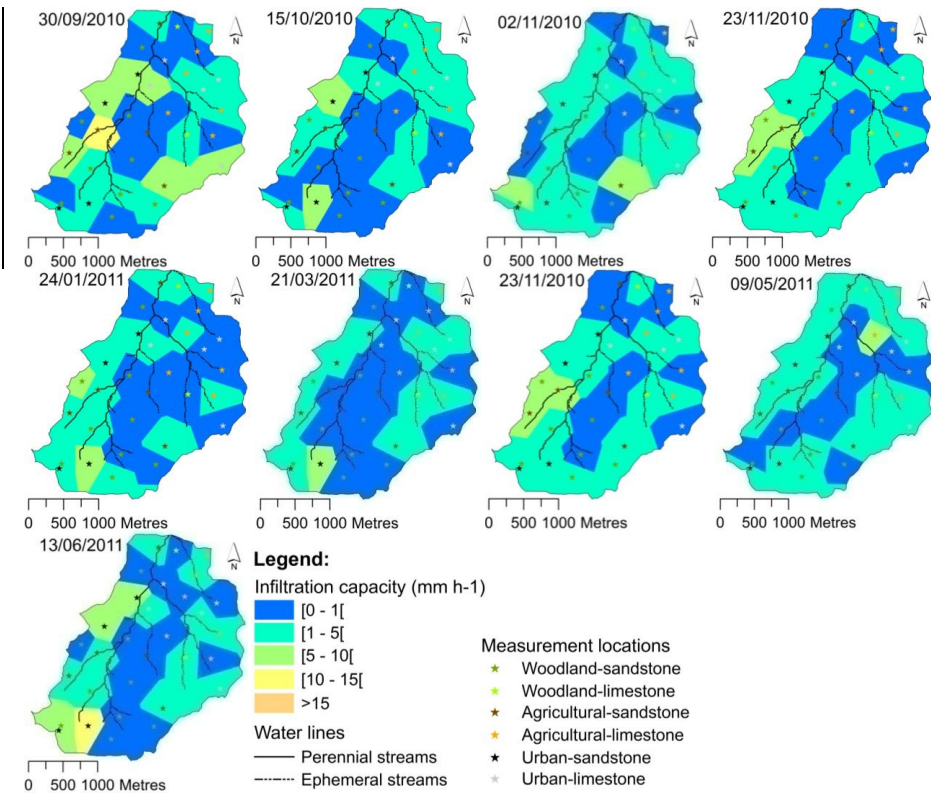


Figure 10 - Spatial variation in median matrix soil infiltration capacity at each measurement dates, using the Thiessen Polygon method.

Table 1 – Rainfall and mean temperature in the days prior to measurement dates.

Formatted

Measurement date	Total rainfall between measurements (mm)	Antecedent rainfall (mm)				Mean temperature during previous 5 days (°C)
		2 days	5 days	10 days	30 days	
30/09/2010	-	0.0	0.0	0.0	5.0	18.9
15/10/2010	72.6	0.0	0.2	53.8	72.6	16.7
02/11/2010	77.2	1.2	75.4	77.2	131.6	14.1
23/11/2010	66.0	0.4	9.6	49.0	141.8	11.4
03/01/2011	161.5	0.5	26	30.2	131.5	12.3
24/01/2011	82.8	0.7	2.6	12.3	112.5	6.9
21/03/2011	97.0	0.2	0.2	15.8	19.8	13.1
09/05/2011	72.328	0.2	3.1	12.5	47.2	16.3
13/06/2011	37.0	0.0	0.0	0.0	37.0	18.1