Paper:

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

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

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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.

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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 restructuration 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.

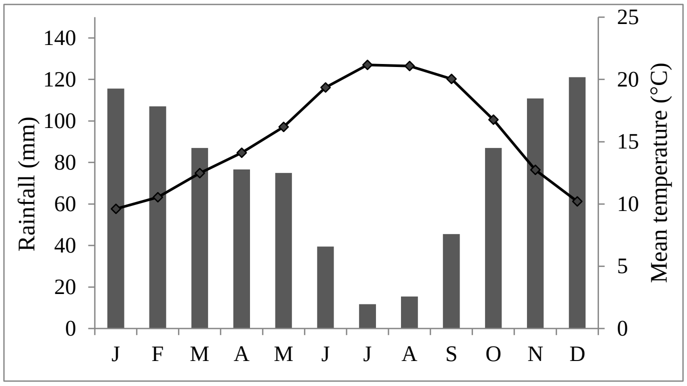
RESPONSE:
The points made by the reviewers are addressed individually below.

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.

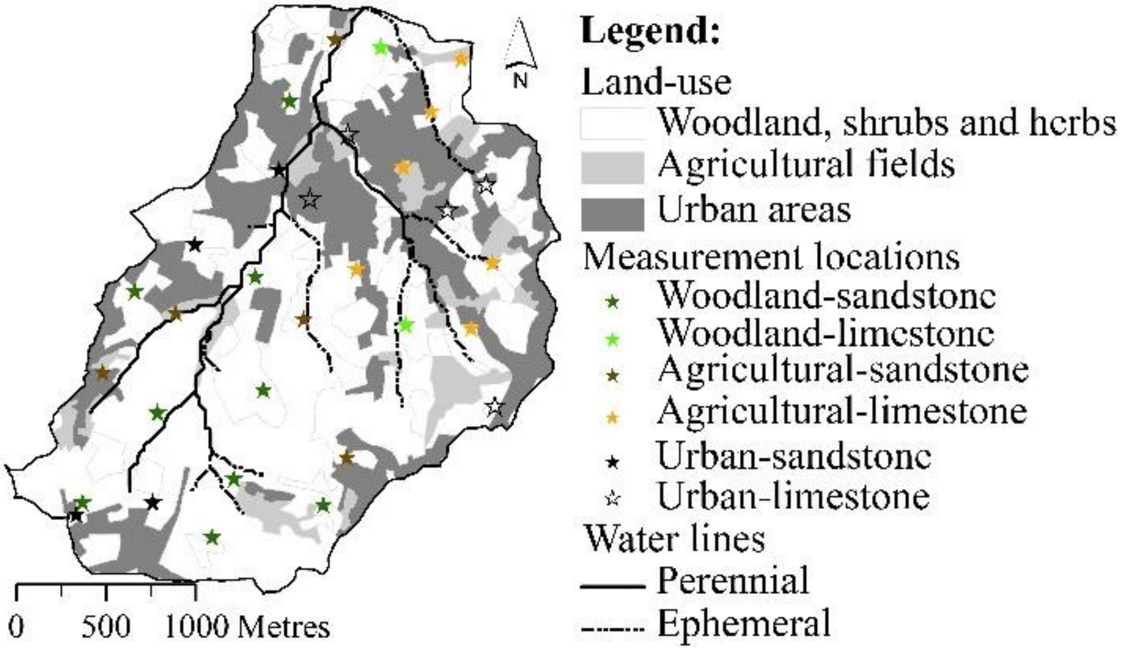
RESPONSE:
Thank you for the endorsement of publishing our manuscript in the Journal of Hydrology.

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.”

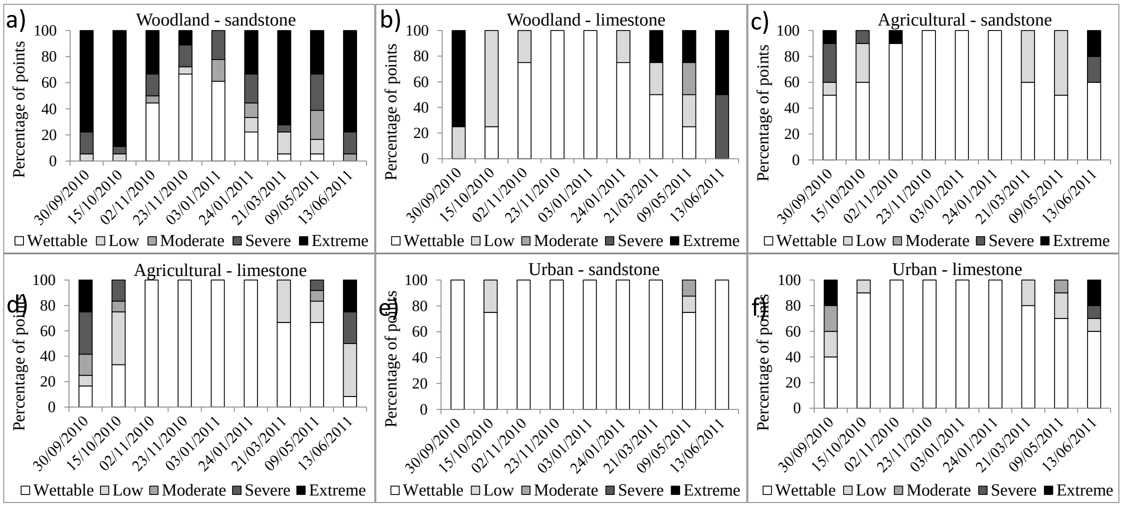
COMMENT:

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 m^2) in extremely hydrophobic woodland soil (slope: 5-36º) (Ferreira et al., 2012b).

On larger runoff plots (16m^2) 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: 6-30º) in 43 mm h^{-1} rainfall simulations on small plots (0.25 m^2) 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, 15-40º) 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, aa 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:

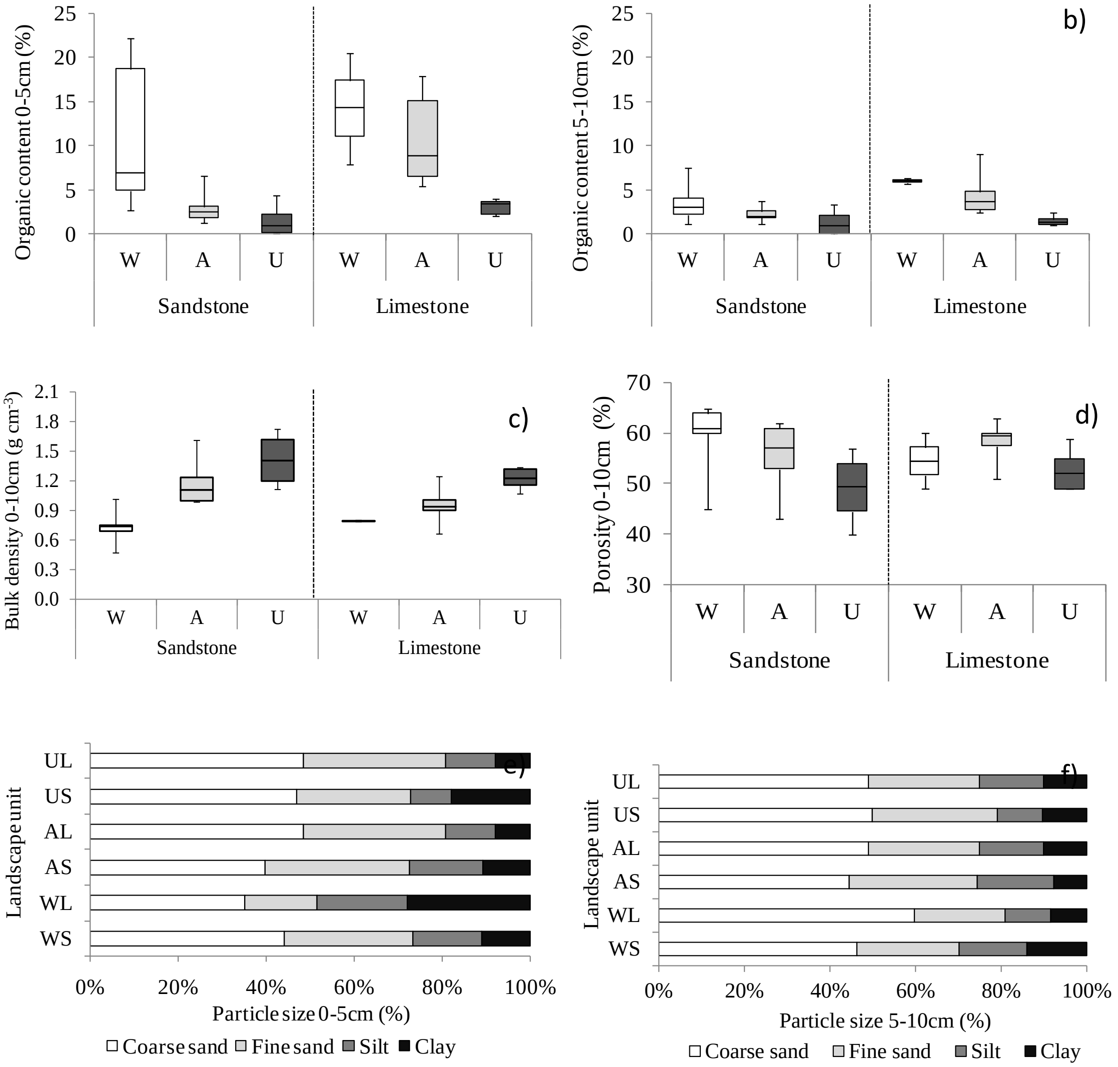
Figure 1: The figure has been changed to show the average values of the entire 1941-2000 period, as explained also to reviewer #1.

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:

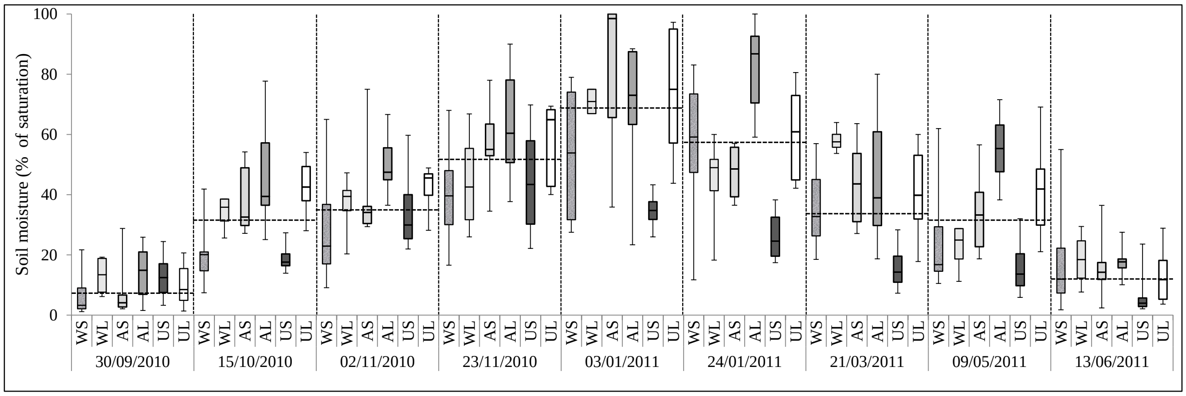


COMMENT:

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:



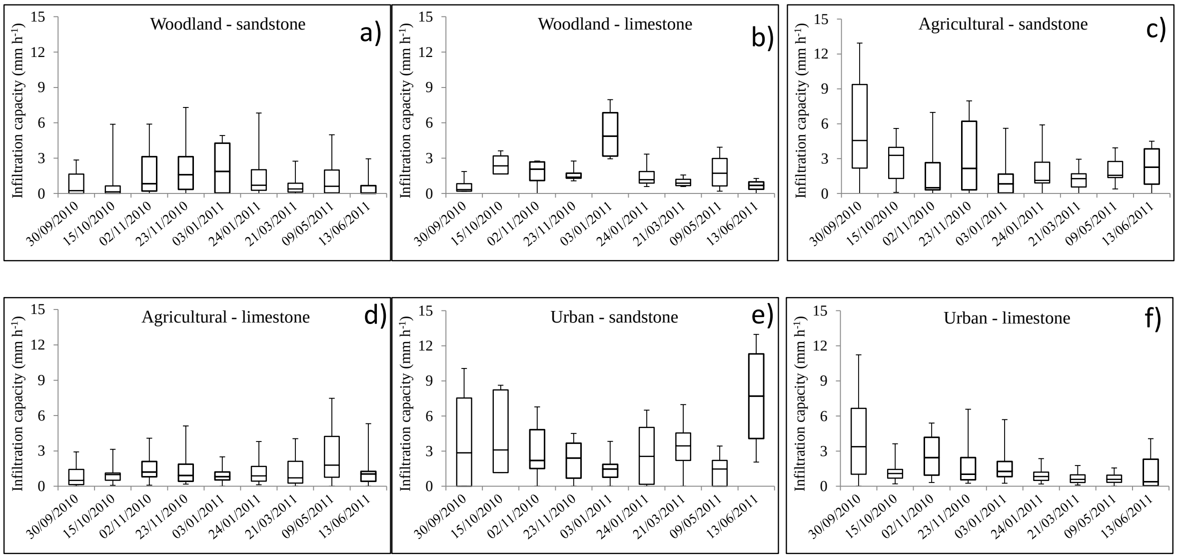
COMMENT:

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 (ºC)
		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

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

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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.

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

1. Introduction

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

Soil moisture, linked to storage capacity, is recognized as a major runoff-controlling factor, particularly in a Mediterranean climate (Cerdà, 1997). Its seasonal variability can mean that greater rainfall intensity is required for overland flow initiation in summer than in winter (Cammeraat, 2002). When saturation overland flow mechanisms are involved, the influence of soil moisture is more varied and not entirely understood, particularly in urbanizing catchments where its spatial and temporal variabilities are rarely reported (Easton et al., 2007).

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 mainly focussed on forested terrain (e.g. Doerr et al., 1996, 1998, 2000; Varela et al., 2005; Keizer et al., 2008; Neris et al., 2013; Nyman et al., 2014). Furthermore, relatively little is known about ‘switching’ between hydrophobic and hydrophilic conditions in dry and wet periods respectively and the net effects on catchment hydrological response in areas affected seasonally by soil hydrophobicity (Leighton-Boyce et al., 2005). In hydrological modelling of urbanizing areas, the phenomenon has not even been considered.

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

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

2. Study area

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

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

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

3. Methodology

3.1 Research design

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

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

Replicate measurements of soil hydrological properties, spaced approximately 1m apart, were carried out at each site. In total, 558 measurements of each parameter were obtained. Three soil samples (c. 100 g each) were collected on the nine occasions at each site to assess surface soil moisture (0-5 cm depth). Additional soil samples were taken at all sites on 23rd November 2010 to determine dry bulk density, rock fragment content, organic matter and particle size distribution. The excavation method (15×15 cm and 10 cm depth) was used for bulk density and rock fragment analyses (three samples per location) (Dane and Topp, 2002). Composite samples were also collected at depths of 0-5 cm and 5-10 cm for organic matter and particle size distribution analyses. Each composite sample comprised 17 sub-samples collected at 15 cm intervals along a 2.4 m transect at each site.

3.2 Field methods and procedure

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

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

3.3 Laboratory methods

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

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

3.4 Data analysis

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

4. Results and analysis

4.1 Soil properties

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

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

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

4.2 Antecedent weather conditions

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

4.3 Soil hydrophobicity

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

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

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

4.4 Soil moisture

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

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

4.5 Infiltration capacity

Soil matrix infiltration capacity in the *Ribeira dos Cov*ões catchment was generally low, despite occasional higher values (Figures 9 and 10). In general, sandstone soils recorded greater permeability than limestone soils. Land-use also affected infiltration capacity but differences varied with season and weather (Figure 9). Generally, woodland recorded higher values in wet than dry periods ($p<0.05$), with median values increasing from 0.1 - 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 the summer, higher infiltration capacity in woodland occurred earlier on limestone than sandstone. Urban soils showed the opposite trend ($p<0.05$), with median infiltration 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 mm h^{-1} on 03/01/2010, with slightly higher values on sandstone than on limestone. In agricultural areas, the fall in median infiltration capacity (from 2.5 mm h^{-1} on 30/09/2010 to 0.8 mm h^{-1} on 03/01/2010) was not statistically significant.

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

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

5. Discussion

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 m^2) in extremely hydrophobic woodland soil (slope: 5-36º) (Ferreira et al., 2012b).

On larger runoff plots (16m^2) 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: 6-30º) in 43 mm h^{-1} rainfall simulations on small plots (0.25 m^2) 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, 15-40º) 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.

5.2 Implications for catchment runoff delivery and land management

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

Vegetation is widely considered as a key factor interrupting hydrological connectivity (e.g. Bracken and Croke, 2007; Appels et al., 2011). Greater vegetation interception provided by woodland and agricultural-limestone areas, compared with the other land-uses, tends to reduce overland flow, though the effect will be marginal in large storm events, when percentage interception is small. The more important effect of interception is in helping (together with transpiration) to reduce antecedent soil moisture levels prior to rainfall events. In central Portugal, 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. In addition, greater litter density and frequency of root holes compared with the other landscape units may lead to enhanced water interception, retention and infiltration, particularly in smaller storm events after dry spells. Surface roughness also enhances water retention and reduces overland flow rates, and promotes discontinuities between overland flow source areas (Rodríguez-Caballero et al., 2012). These infiltration/retention processes operating at larger scales, as well as preferential flow via root-holes and cracks, considerably reduce the risk that overland flow from low permeable soil sites might reach downslope contiguous urban areas and/or the stream network. Although urban soils may provide overland flow sinks, the impermeable tarmac and paved surfaces allow little infiltration, restricting the capacity of these areas to deal with rainfall and overland flow from upslope landscape units. Observations in *Ribeira dos Covões* over three years suggest that only small amounts of overland flow were generated in woodland and agricultural limestone areas, mainly after dry conditions. Nevertheless, 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).

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

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

Because of the generally low infiltration capacity or saturated condition of downslope urban soil areas, saturation overland flow reaching such areas may be problematic, although this can be offset by spatial differences in modified and unmodified soil properties providing a mosaic of different infiltration capacities. 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. This will depend on urbanization style, since extended impermeable surfaces will enhance landscape connectivity, whereas detached houses surrounded by gardens and walls can provide sinks and flow discontinuity.

The susceptibility of urban core areas located in topographic lows (Figure 2b) to saturation overland flow and stream flooding may represent a real flood hazard for the inhabitants, particularly considering the scale of recent urban consolidation in the *Ribeira dos Covões* catchment. This risk may be enhanced by 1) additional overland flow resulting from greater connectivity with upslope areas subject to soil moisture increase and water table rise, and 2) the rapid transfer of most overland flow from upslope impermeable surfaces directly into the stream via the urban drainage system. These may be particularly important in larger storm events, considering the generally low soil permeability across the catchment. 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 now.

Analyses of storm hydrographs of the outlet stream (results not shown) suggest that the actual landscape mosaic of *Ribeira dos Covões* catchment, comprising extensive woodland areas and large urban areas near the catchment outlet, together with numerous smaller urban areas mainly along ridges and dispersed agricultural fields (Figure 2b), may be sufficient to promote discontinuities to the infiltration-excess overland flow generated by soil hydrophobicity. Thus, in dry settings, rainstorms of 2.8 mm (average) and 14.4 mm (large), recorded on 6th August and 1st September 2011, promoted runoff coefficients for the *Ribeira dos Covões* stream of only 5% and 2% respectively and peak streamflows of only 0.041 mm h^{-1} and 0.036 mm h^{-1}, compared with maximum 5-minute rainfall intensities of 2.4 mm h^{-1} and 9.6 mm h^{-1} respectively. Thus, hydrophobicity over the catchment does not translate into catchment-scale overland flow, presumably due to infiltration into sinks downslope. In wet conditions, however, enhanced soil moisture levels seem to increase flow connectivity over the catchment. Thus rainstorms of 2.8 mm and 15.0 mm registered on 11th February and 28th March 2011, led to 10% and 9% storm runoff coefficients and peak flows of 0.079 and 0.370 mm h^{-1}, compared with maximum rainfall intensities of 9.6 mm h^{-1} in both cases. Although lag times from peak rainfall to peak streamflow are short, ranging between 25 and 35 minutes, and probably a direct result of urban surface runoff and the urban drainage system, the overriding feature is the small size of the storm runoff coefficients both during dry and wet times of the year, which shows how little of the rain falling on the peri-urban mosaic actually reaches the stream network. This may reflect in part the ridge location of much of the urban expansion to date and in part a rather high proportion of infiltration into urban soil within the urban units and adjacent landscape units.

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

5 Conclusions

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

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

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

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

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

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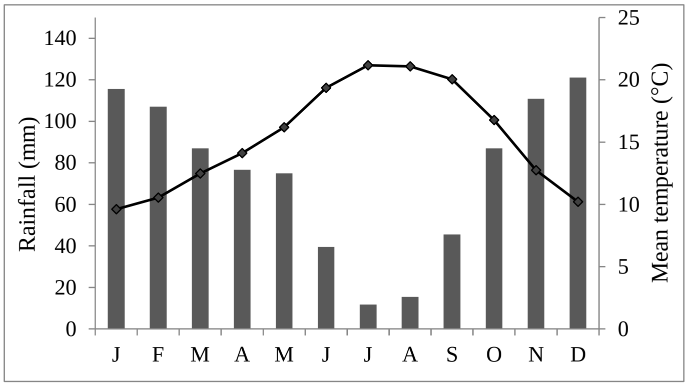

Figure 1 – Average monthly rainfall and temperature at Coimbra (Bencanta weather station), calculated from data regarding to the period 1941-2000 (INMG, 1941-2000).

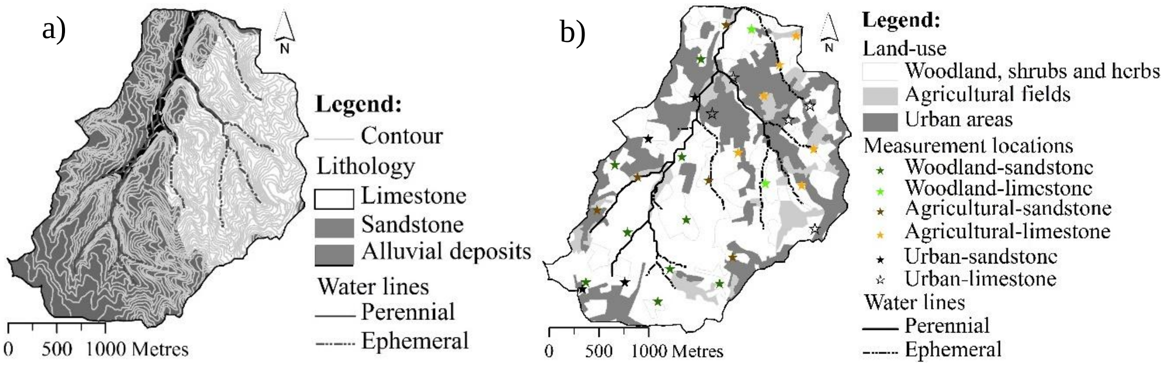

Figure 2 – *Ribeira dos Covões* catchment: (a) topography, lithology and streams; (b) land-use in 2009 and location of the study sites.

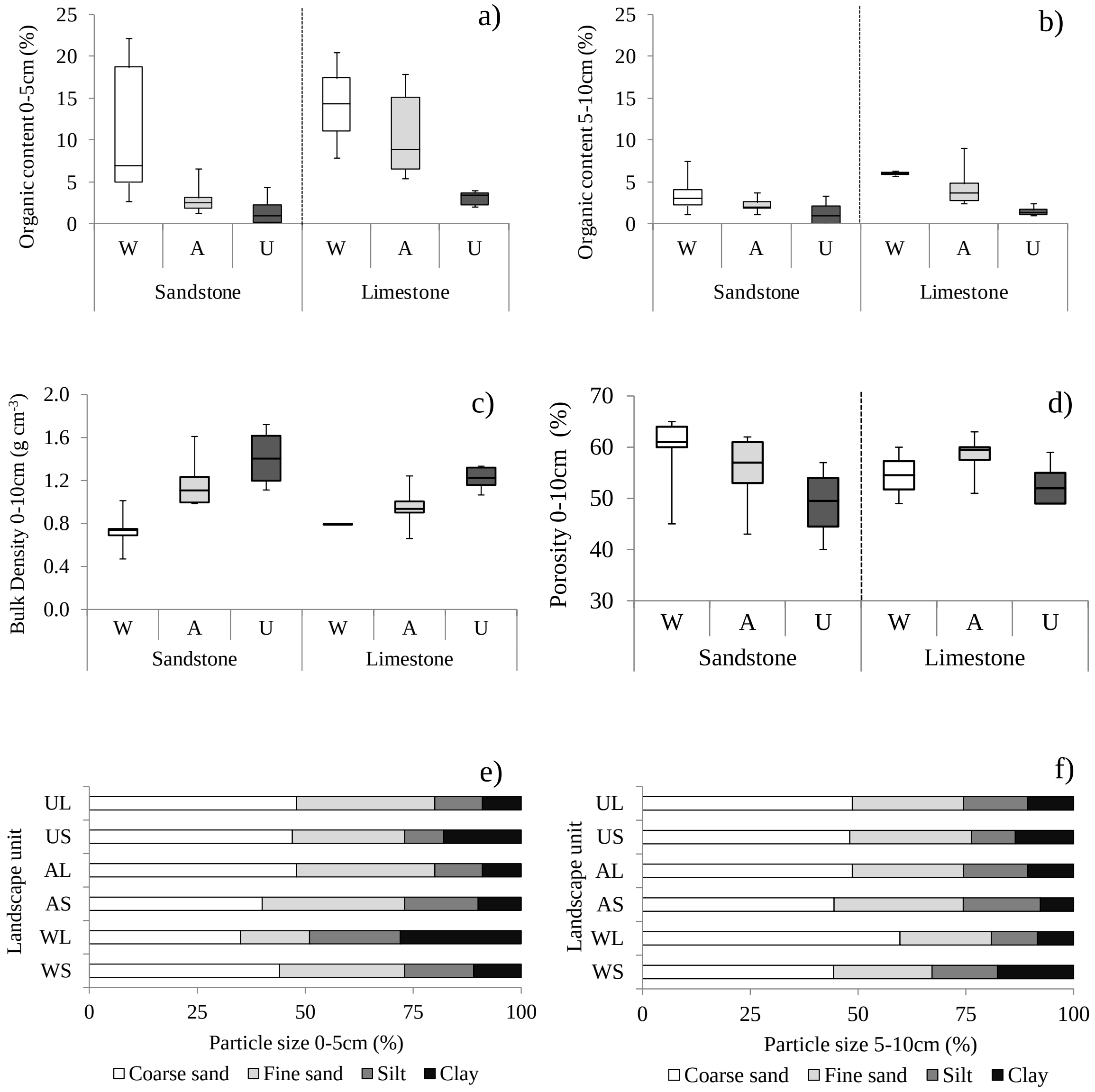

Figure 3 – Soil properties in different landscape units: a) organic matter content at the surface (0-5cm) and b) subsurface (5-10cm), c) bulk density (0-10cm), d) porosity (0-10cm), e) particle size distribution of surface (0-5cm), and f) subsurface soil (5-10cm) (W: woodland, A: agricultural, U: urban,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

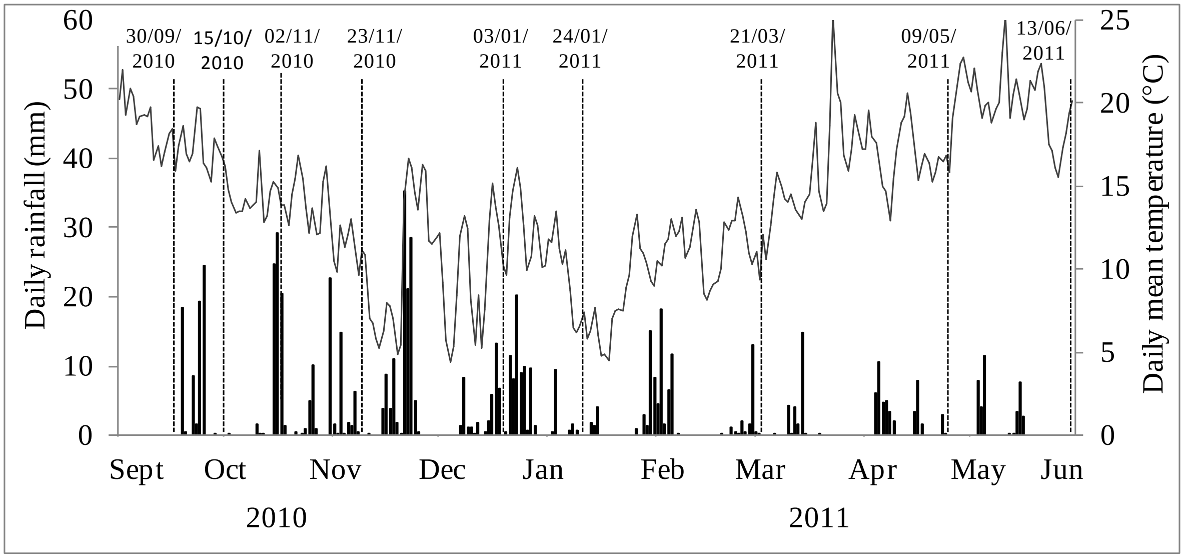

Figure 4 – Daily rainfall and mean daily temperature during the monitoring period September 2010 – May 2011 with dates of field measurements.

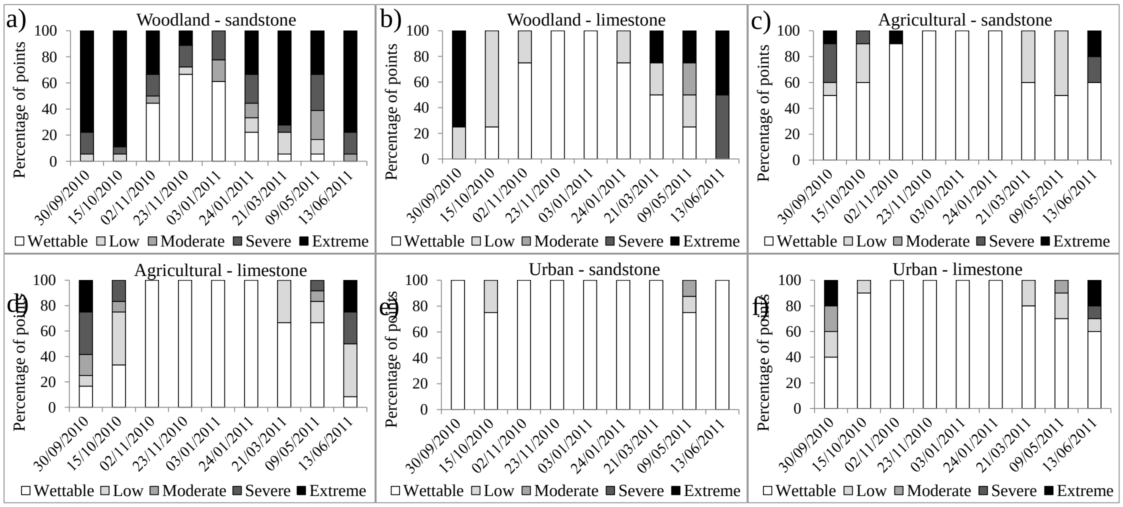

Figure 5 – Temporal variability of surface hydrophobicity for individual landscape units: a) woodland-sandstone, b) woodland-limestone, c) agricultural-sandstone, d) agricultural-limestone, e) urban-sandstone, f) urban-limestone.

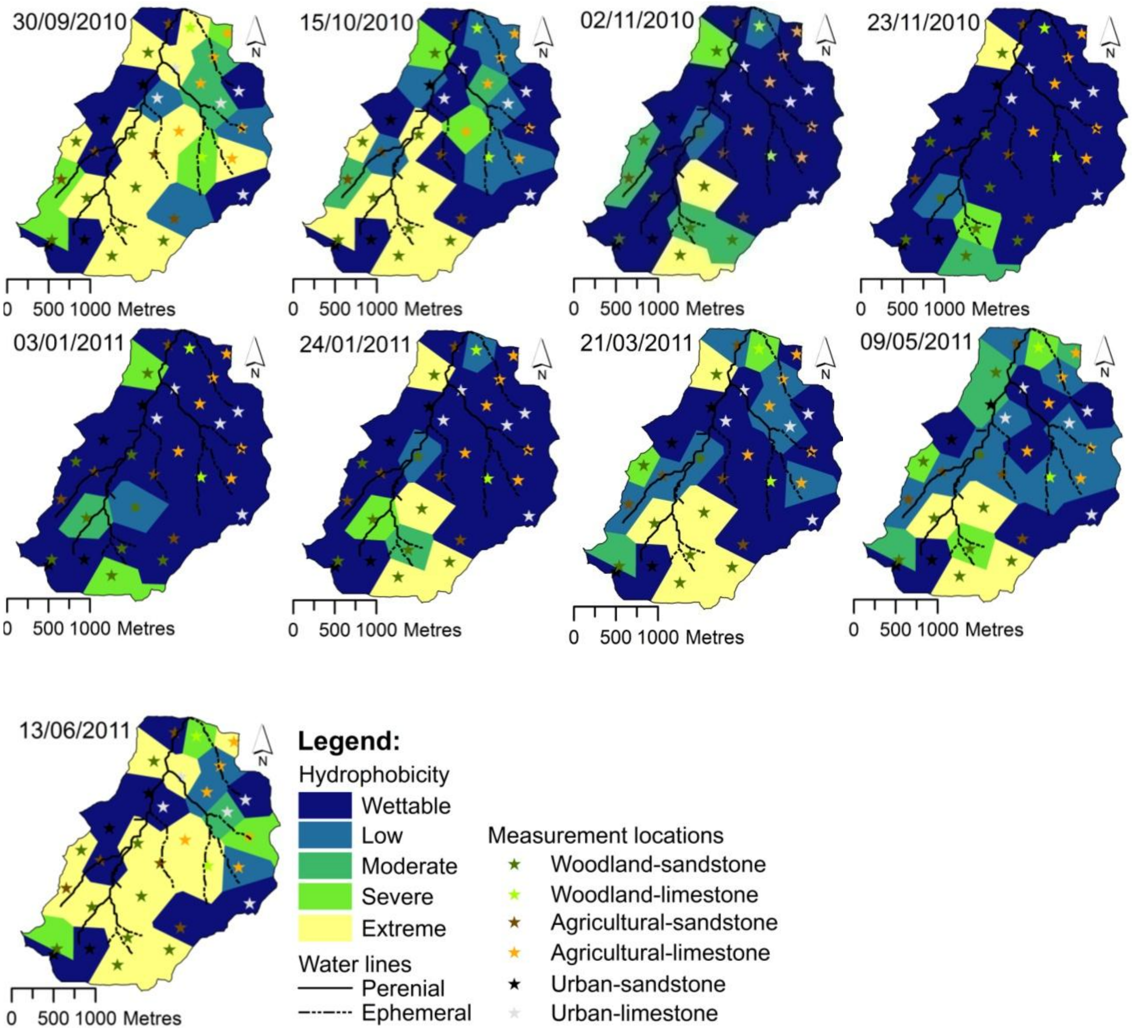

Figure 6 – Spatial variation of median soil hydrophobicity at the measurement dates, based on the Thiessen polygon method.

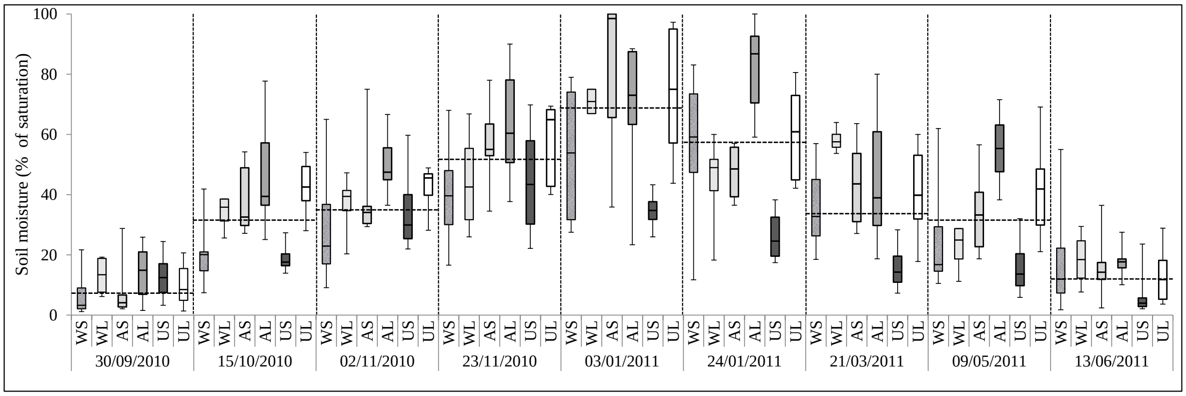

Figure 7 – Box-plots of soil moisture content for the different landscape units for the study period (W: woodland, A: agricultural, U: urban, S: sandstone, L: limestone). Horizontal dashed lines represent median soil moistures across the catchment, for the 9 measurement dates.

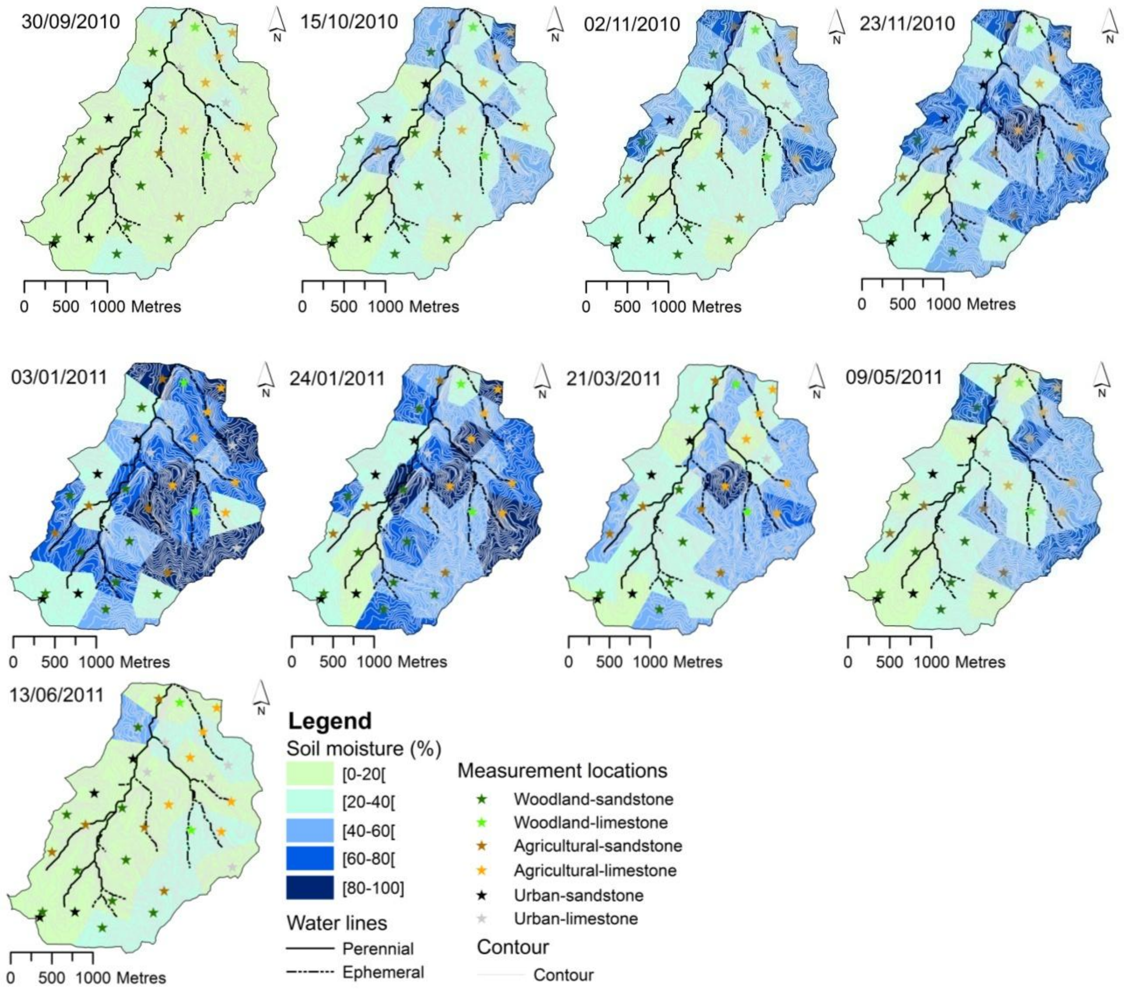

Figure 8 – Spatial distribution in median soil moisture content for each the measurement date, using the Thiessen polygon method.

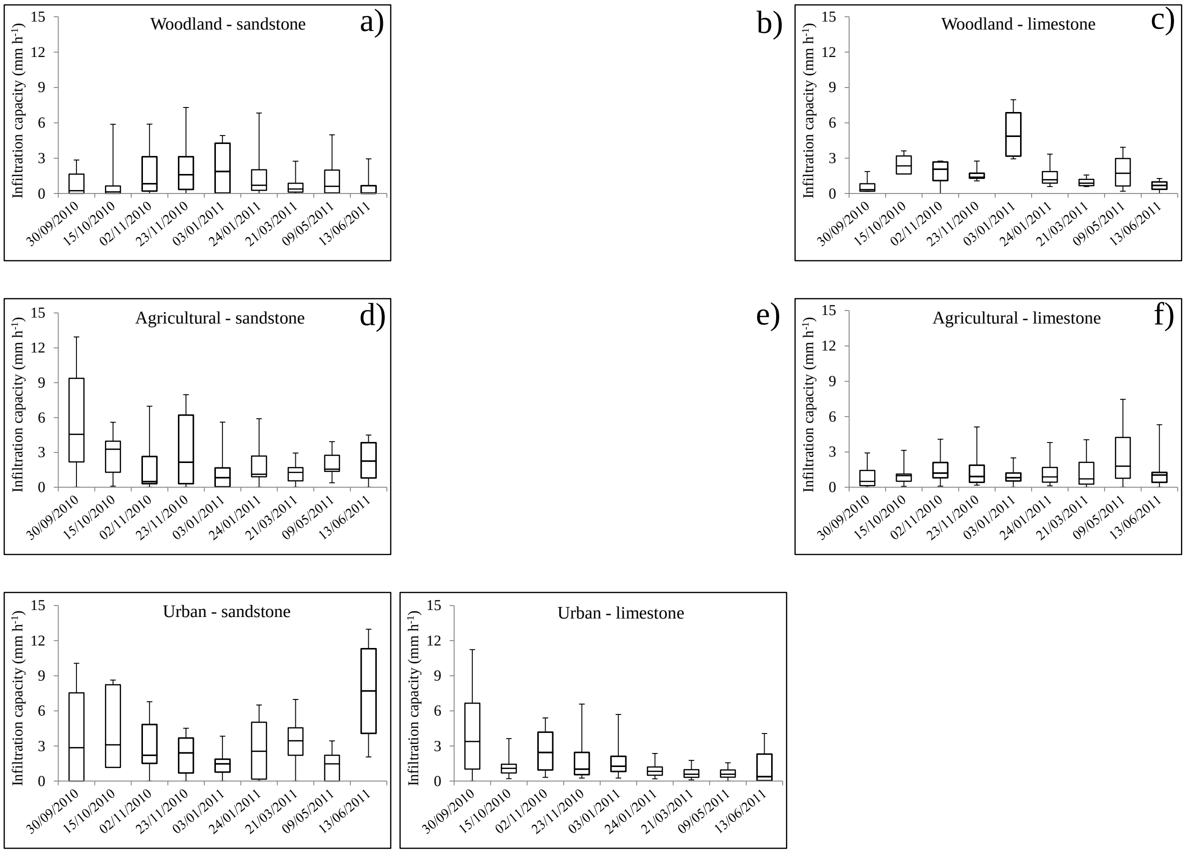

Figure 9 – Box plots of temporal variability of matrix soil infiltration capacity for each landscape unit: a) woodland-sandstone, b) woodland-limestone, c) agricultural-sandstone, d) agricultural-limestone, e) urban-sandstone, f) urban-limestone.

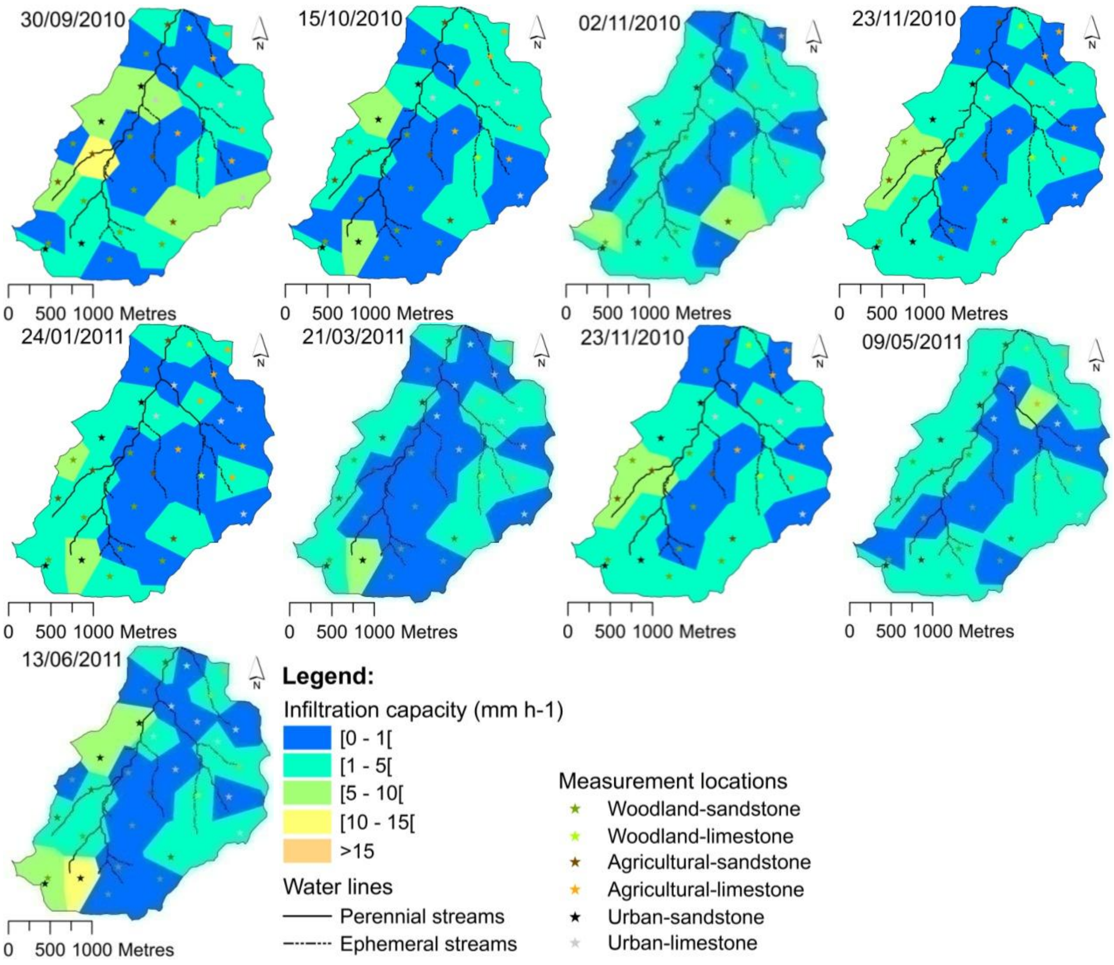

Figure 10 - Spatial variation in median matrix soil infiltration capacity at each measurement date, using the Thiessen Polygon method.

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 (ºC)
		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

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

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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 ~~sub-~~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~~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 ~~the~~ forest~~woodland~~ on both sandstone and lime~~-~~stone and on agricultural soils on limestone~~,~~ due probably in large part to soil hydrophobicity~~to soil hydrophobicity~~. In wet periods, ~~saturation excess~~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 ~~upland~~ upslope source areas potentially can infiltrate in other landscape units downslope~~hill~~ where ~~with~~ infiltration capacity exceeds~~in excess of the~~ rainfall intensity~~ies~~. 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.

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

1. Introduction

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

~~The combined effect of these factors is one of the most important factors related to land-use change impacts on hydrology. In addition, s~~Soil moisture, linked to storage capacity, is recognized as a major runoff-controlling factor, particularly in a Mediterranean climate (Cerdà, 1997). Its seasonal variability can mean that greater rainfall intensity is required for overland flow initiation in summer than in winter (Cammeraat, 2002). When ~~saturation-excess~~saturation overland flow mechanisms are involved, the influence of soil moisture is more varied and not entirely understood, particularly in urbanizing catchments where its spatial and temporal variability are rarely reported (Easton et al., 2007).

Although ~~T~~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), ~~but~~ in areas of Mediterranean climate they have ~~been~~ mainly focussed~~confined to~~ on forested terrain ~~locations~~ (e.g. Doerr et al., 1996, 1998, 2000; Varela et al., 2005; Keizer et al., 2008; ~~Shakesby, 2011;~~ Neris et al., 2013; Nyman et al., 2014). Furthermore, r~~R~~elatively little~~, however,~~ is known about ‘switching’ between hydrophobic and hydrophilic conditions in dry and wet periods respectively and the net effects on catchment hydrological response in areas affected seasonally by soil hydrophobicity (Leighton-Boyce et al., ~~2002~~2005). In hydrological modelling of urbanizing areas, the phenomenon has not even been considered.

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

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

2. Study area

The study site is the S-N elongated *Ribeira dos Covões* catchment (40°13'N, 8°27'W; 6.2 km^2) in the suburbs of Coimbra, the largest city of central Portugal. The climate (as recorded at Bencanta, 0.5 km north of the catchment boundary) is humid Mediterranean, with a mean annual temperature of 15ºC, a mean annual rainfall of 892 mm (INMG, 1941-2000), hot and dry summers (~~only~~ 8% of rainfall in the months June-August) and wet winters (Figure 1). The main watercourse is perennial, supplied by several springs, and there are several smaller ephemeral tributaries (Figure 2). The geology (Figure 2a) comprises Jurassic dolomitic and marly limestone in the east (49% of the catchment area), and Cretaceous and Tertiary sandstones, conglomerates and mudstones in the west (47% of the area), with some Pliocene-Quaternary sandy-conglomerate (~~sediment~~colluvium) and alluvial deposits (4% of the area) in the main valleys. Soils are generally deep (>3m) Cambisols and Podzols (Tavares et al., 2012). Only on steeper slopes in the northwest is soil depth less than~~<~~40 cm. Altitude ranges from 29m to 201m. The average slope is 9º, but ~~with ~~a few slopes reach~~ing~~ up to 46º.

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

3. Methodology

3.1 Research design

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

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

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

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

3.2 Field methods and procedure

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

Near each infiltrometer location, soil hydrophobicity was assessed at depths of 0, 2 and 5cm using the Molarity of an Ethanol Droplet (MED) technique (~~Letey, 1969;~~ Doerr et al., 1998). Fifteen drops of ~~pure~~ distilled water and then progressively higher concentrations of ethanol were applied until the lowest concentration was identified at which at least 8 out of 15 drops were absorbed within 5 seconds. Ethanol concentrations of 0, 3, 5, 8.5, 13, 18, 24 and 36 percent by volume were used. The soil was considered wettable (hydrophilic) when ~~pure~~ distilled water drops infiltrated within 5 seconds. The~~;~~ ~~hydrophobicity~~ classes of levels of hydrophobicity used were: low for 3 and 5% ethanol, moderate for 8.5 and 13%, severe for 18 and 24%, and extreme for 36% (Doerr et al., 1998).

3.3 Laboratory methods

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

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

3.4 Data analysis

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

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

4. Results and analysis

4.1 Soil properties

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

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

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

4.2 Antecedent weather conditions

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

4.3 Soil hydrophobicity

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

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

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

4.4 Soil moisture

Surface soil moisture varied with antecedent weather (Figures 7 and 8), increasing after rainfall (although correlations were weak: r=0.375, 0.168, 0.258 and 0.541 with ~~-~~2-, 5-, 10- and 30-~~—~~day antecedent rainfall, respectively, p<0.001)~~,~~ and declining with higher temperature (r=-0.593 with values in previous 5 days, p<0.001). During summer and after long rain-free periods (30/09/~~3010~~ 2010 and 13/06/2011), soil became dry (<20% moisture) across the catchment.

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

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

4.5 Infiltration capacity

Soil matrix infiltration capacity in the *Ribeira dos Cov*ões catchment was generally low, despite occasional higher values (Figures 9 and 10). In general, sandstone soils recorded greater permeability than limestone soils. Land-use also affected infiltration capacity but differences varied with season and weather (Figure 9). Generally, woodland recorded higher values in wet than dry periods ($p<0.05$), with median values increasing from 0.1 - 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 the summer, higher infiltration capacity in woodland occurred earlier on limestone than sandstone. Urban soils showed the opposite trend ($p<0.05$), with median infiltration 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 mm h^{-1} on 03/01/2010, with~~and showing~~ slightly higher values on sandstone than on limestone. In agricultural areas, the fall in median infiltration capacity (from 2.5 mm h^{-1} on 30/09/2010 to 0.8 mm h^{-1} on 03/01/2010) was not ~~n~~ statistically significant.

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

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

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

5. Discussion

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

~~Interpretation of soil properties~~

5.1.1 ~~Organic matter, bulk density and particle size~~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 ~~E~~eucalypt~~-dominated~~ than other woodlands~~ areas tended to have relatively low organic matter, possibly~~ may reflect~~ing~~ (a) periodic understorey clearance to help prevent wildfires and (b)~~, but also~~ low understorey vegetation caused by reduced water availability (DeBano, 2000). ~~The denser root system associated with larger vegetation cover may favoured low values of soil bulk density~~. 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~~woodland units may the outcome of the higher organic matter than of other landscape units~~ and the denser root systems associated with a tree cover. Reduced bulk density is also characteristic of~~was reported in~~ soils with greater organic matter, since it helps the formation of soil aggregates and structure (Celik et al., 2010).

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

~~sandstone areas, larger number of rainfall events were also required for the soil became hydrophilic, and even during the wettest settings, hydrophobicity persisted in few soil spots. Hydrophobicity is caused, notably, by the hydrophobic substances released by vegetation.~~ The type of resins, waxes and aromatic oils ~~of~~produced by eucalypt (Doerr et al., 1998; Jordán et al., 2008) ~~woodland~~ is thought to have caused hydrophobicity to be more extensive and resistant than in the other woodland stands, with hydrophobicity ~~.~~ ~~Previous studies reported hydrophobicity, particularly~~ in eucalypt stands~~, was~~ able to persist following rainfall of as much as 200mm in 2 months (Ferreira, 1996; Doerr and Thomas, 2000). In contrast, ~~I~~in woodland-limestone areas, hydrophobicity was less severe and easier to switch to hydrophilic conditions 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 quicker re-establishment of hydrophobic conditions after rainfall events, comparing with the other landscape units, particularly under eucalypt plantations. The rate of re-establishment would depend 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) report greater dynamism, and more frequent hydrophobic conditions in eucalypt than in pine.

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

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

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

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 ~~Previous studies elsewhere also showed~~ the inconsistent results recorded elsewhere. ~~and denoted that the existence of a threshold may be illusive, despite useful to understand hydrophobicity and their potential impacts on hydrological processes.~~ Thus ~~I~~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 ~~lower water affinity provided by greatest~~ in hydrophobicity of woodland areas would explain seasonal contrast in ~~could have led to limited~~ infiltration capacity ~~during dry periods~~. ~~U~~Thus, under driest conditions, when hydrophobicity is widespread on woodland soil, ~~and~~ measured infiltration capacity was~~is~~ minimal, whereas~~.~~ ~~However,~~ in wettest conditions, the limited spatial extent of hydrophobicity allowed infiltration capacity of woodland sites to attain the 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~~be~~ because infiltration ~~sometimes~~ may sometimes have been ~~is~~ delayed by repellency, but on other occasions have commenced with switching to hydrophilic conditions by the end of the final 10 minutes of the~~and the soil may not have reached steady state infiltration rate conditions after~~ 30 minutes measurement period.

Organic matter arguably plays a dual role in explaining 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~~O~~ levels of organic matter ~~is usually~~ promote~~ associated with~~ structured soils of high matrix infiltration capacity, representing the more typical situation of forest soils (e.g. Costa, 1999; Mouri et al., 2011.~~)~~. ~~Nevertheless, with hydrophobicity banishment through autumn and winter seasons, as a result of increasing rainfall, matrix infiltration capacity of woodland areas raised, attaining the highest values in January, and denoting the high permeability usually associated with forest soils (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 ~~eucalyptus~~eucalypt and pine areas and resultant very low matrix infiltration capacity makes the woodland-sandstone areas particularly susceptible to infiltration-excess overland flow generation. The less hydrophobic nature of the predominantly oak vegetation of woodland-limestone areas means that they are less prone to infiltration-excess overland flow.

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

~~infiltration-excess overland flow generation in succeeding rainstorms. In urban and agricultural-sandstone areas, greater infiltration capacity under the same conditions (Figure 10) made these areas overland flow sinks. In woodland and agricultural-limestone areas, however, p~~ Prolonged or repeated rainfall events lead to partial switching of woodland soils to a hydrophilic state, and reductions in ~~hydrophobicity severity and~~ spatial extent and severity of hydrophobicity~~, and enhancement of infiltration capacity~~. Hydrophobicity in ~~eucalyptus~~eucalypt stands is more resistant to break down, 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~~ (Figure 9)~~. In prolonged wet weather of the winter wet 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.

~~In prolonged wet weather, hydrophobicity disappeared and infiltration capacity increased even in woodland,~~

The potential for infiltration-excess overland flow in ~~urban and~~ woodland landscape units~~soils~~ in dry summer conditions was confirmed by rainfall simulation experiments,~~.~~ ~~performed in the study area, but not on agricultural soils. Hour-long experiments simulating~~ when a 43 mm h^{-1} simulated rainfall ~~(a typical maximum reached over several years) in a small plot (0.25m^{2})~~ produced runoff coefficients of ~~of 59-99% on wettable urban soils~~

~~(slope: 6-30º),~~ 20-83% in a small plot (0.25 m^2) in extremely hydrophobic woodland (slope: 5-36º) ~~, but 0% on wettable agricultural land (slope 15-50º)~~ (Ferreira et al., 2012~~c~~b).

Under natural rainfall~~, however,~~ in larger runoff plots ($16m^2$) in woodland, however, ~~installed in woodland areas showed that even~~ under extremely hydrophobic conditions, overland flow did not exceed 3% even for a 23mm rainfall event (Ferreira et al., 2012a), mainly because of~~. High water~~ infiltration bypassing the~~in a~~ hydrophobic soil matrix ~~may be explained by preferential flow~~ via macropores that can be provided by~~, for example,~~ root-holes, invertebrate activity and high concentrations of stones (e.g. Urbanek and Shakesby, 2009; Hardie et al., 2011). Such bypass (preferential) flow~~and~~ is viewed as an important mechanism not only in ~~both~~ 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). Cracks in clay soils were observed in dry conditions during fieldwork in the catchment study.

~~Nevertheless, in *Ribeira dos Covões*, even under the wettest winter conditions, woodland areas showed relatively low soil moisture and high infiltration capacities, indicating their potential to act as sinks in absorbing overland flow from upslope.~~

5.~~2~~1.2~~.~~ Urban landscape units

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

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

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

The generally hydrophilic conditions found in ~~over~~ urban soil~~environments~~ would help to explain~~favour~~ the high soil matrix infiltration capacity values ~~isty and may explain the great values~~ recorded particularly after prolonged dry weather~~over dry setting~~s (Figure 9), despite~~. High infiltration capacity of the urban soils was not expected considering~~ the ~~upper the~~ high bulk density,~~,~~ ~~despite no significant correlation was found between both variables.~~ which elsewhere has been noted to be associated with ~~L~~lower infiltration capacities~~y associated with higher bulk density linked to urban activities has been noted elsewhere~~ (e.g.

Dornauf and Burghardt, 2000; Yang and Zhang, 2011). ~~Nevertheless, with increasing soil moisture content over the wet periods,~~ The very low and in some cases zero values of soil matrix infiltration capacity ~~was reduced and attained even null values in few spots.~~ recorded ~~Decreasing infiltration capacity under~~ during wet periods~~wet setting is because of~~may be linked to a decline in the suction force and then saturation of the ~~often thin~~ soil ~~(Costa, 1999)~~. The inverse correlation recorded between soil moisture and infiltration capacity ~~for urban soils these variables~~ was also found~~reported~~ in Tasmania, Australia, where the application of dye tracer ~~in low antecedent soil moisture~~ 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~~t~~ a wetting front velocity of 120 mm h^{-1}) with wet antecedent conditions (Hardie et al., 2012).

In urban landscape units, overland flow is readily generated on paved and tarmac impervious 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 locally being generated. In contrast, in urban soils on sandstone, soil 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.

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

The potential for ~~infiltration-excess~~ overland flow generation in urban~~ and woodland~~ soils was demonstrated by runoff coefficients of 59-99% recorded on hydrophilic urban soils (slope: 6-30º) in~~confirmed by rainfall simulation experiments performed in the study area, but not on agricultural soils. Hour-long experiments simulating a~~ 43 mm h^{-1} rainfall simulations~~(a typical maximum reached over several years) in a~~ on small plots ($0.25 m^2$) at the field sites, though it was unclear whether the overland flow was infiltration-excess or ~~saturation-excess~~saturation in nature ~~produced runoff coefficients of 59-99% on wettable urban soils (slope: 6-30º), 20-83% in extremely hydrophobic woodland (slope: 5-36º), but 0% on wettable agricultural land (slope 15-50º)~~ (Ferreira et al., 2012~~c~~b).

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5.1.3 Agricultural landscape units

In agricultural landscape units~~areas~~, different ~~stinct~~land-use/land management types lead to~~imprint~~ major differences on surface cover and soil properties. The ~~A~~agricultural types~~fields~~ on~~verlaying~~ sandstone ~~include~~ (mainly pasture, small gardens and olive~~ tree~~ plantations)~~. This agricultural practices~~ may explain the low organic matter content and~~ the~~

high bulk density results of that landscape unit compared with the agricultural-limestone unit, where~~n compared with the contrasting~~ abandoned fields undergoing natural vegetation succession are~~,~~ dominant.~~ on limestone, with vegetation following the natural succession.~~ This greater vegetation cover with higher soil organic matter content for~~under~~ agricultural-limestone would also explain the unit's enhanced~~ hydrophobic properties, linked to higher~~ spatial extent and severity than on sandstone~~agricultural-sandstone soils~~. Nevertheless~~However, considering the lower vegetation cover and the dominance of more Mediterranean herbaceous and scrub species,~~ hydrophobicity at~~in~~ agricultural-limestone sites was less~~not so~~ severe ~~as~~than in woodland, and fewer~~less~~ rainfall events were required to accomplish~~stimulate the~~ switching ~~pattern between~~from hydrophobic to~~and~~ hydrophilic conditions~~haracteristics.~~ and~~ In agricultural-limestone fields, the~~ hydrophobicity re-establishment in~~during~~ 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~~stability~~ when conditions were changing from dry to wet.

~~In~~ The generally~~, agricultural areas showed~~ greater soil moisture values~~content~~ of agricultural~~ when~~ compared with ~~the ~~other landscape units~~land uses~~, despite the absence~~lack~~ of irrigation,~~.~~ ~~This ~~may be explained by the lower vegetation cover of the agricultural-limestone sites and the low hydrophobicity, particularly when compared with woodland. In addition, high surface roughness associated with tillage in agricultural-sandstone fields~~, mostly favoured by tillage practices,~~ 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 ~~only~~ slightly higher at agricultural-limestone than agricultural-sandstone sites, despite most of the former being abandoned. This may be ~~could possibly be~~ a consequence of the marly nature of the limestone, which leads to~~soil properties differences, coupled with~~ greater fractions of fine material. ~~inn agricultural-limestone areas. Furthermore~~, ~~That~~However, the small soil moisture difference ~~is small~~ may reflect the fact that most sandstone agricultural sites are on valley floors (Figure 8).~~,~~ whereas limestone sites are mainly on upper slopes, where the soil is shallow (generally <40cm depth), 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, coarser particle size distribution and minor hydrophobicity ~~is likely to provide~~ may explain greater soil matrix infiltration capacity on sandstone compared with limestone agricultural areas in dry periods.

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

Overland flow generation, in response to the contrasts in soil moisture, hydrophobicity and infiltration capacity and their seasonal dynamics discussed above, differed between the agricultural-sandstone and agricultural-limestone landscape units. In agricultural-sandstone areas, high infiltration capacities associated with hydrophilic soils throughout the year and with sandy particle size 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.

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

~~The potential for~~ Unlike on urban and woodland soil sites, no infiltration-excess overland flow ~~in urban and woodland soils was confirmed by~~ was recorded in 43 mm h^{-1} rainfall simulation experiments ~~performed in the study area, but not on agricultural soils. Hour-long experiments simulating a 43 mm h^{-1} rainfall (a typical maximum reached over several years) in a small plot (0.25m^{2}) produced runoff coefficients of 59-99% on wettable urban soils (slope: 6-30º), 20-83% in extremely hydrophobic woodland (slope: 5-36º), but 0% on wettable~~ on hydrophilic agricultural land (slope 15-50º) in the study area (Ferreira et al., 2012~~c~~b).

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

5.1.4 Synthesis: the influences of lithology, topography and land-use factors on overland flow and temporal variation in its distribution~~controls~~ within the Ribeir~~o~~a dos Covõ~~o~~es catchment

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

Secondly local topographic characteristics also seem to be an important driver. 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, Latron and Gallart (2007), also explained the saturation pattern with 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 constitutes 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.~~In fact, these soil properties seems to be particularly affected by the land-use and management practices, which lead to the division of the l~~ 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 ~~eucalyptus~~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, but which for lithology-related reasons can 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 from 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-excess~~saturation overland flow as soil moisture declined (mainly associated with agricultural- and urban-limestone areas) and increasing vulnerability to infiltration-excess overland flow, enhanced by hydrophobicity re-establishment (particularly in woodland but also on agricultural-limestone).~~.~~ 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 locally or more widespread 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 ~~eucalyptus~~eucalypt parts 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 the partly bare urban-sandstone unit and woodland and agricultural-limestone units in transitional periods ~~-~~(Figure 9). Soil spots with matrix infiltration capacity lower than rainfall intensity will lead to infiltration-excess overland flow, which may be infiltrated in surrounding soil spots with greater infiltration capacity. ~~Only the few most permeable soil patches found in the landscape units could cope with a rainfall intensity of 5.4 mm h^{-1}, the mean hourly rainfall intensity of storm events >5mm recorded in the years 2010-2011.~~ Not all the 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 wettest conditions, woodland provided sites of high infiltration capacity. ~~The generally higher permeability of sandstone than limestone areas highlights the former's lower potential for infiltration-excess overland flow generation.~~ 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.

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

~~Despite the spatiotemporal variability as regards to the land-use and lithology impacts on soil moisture,~~ ~~-local topographic characteristics seems to be an important driver. 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, Latron and Gallart (2007), also explained the saturation pattern with extent and height of the water table. The locations and sizes 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 areas (Easton et al., 2007).~~

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

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

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

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

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

~~5.1.2 Soil hydrophobicity~~

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

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

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

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

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

~~The weak, albeit significant correlation found between hydrophobicity and soil moisture is attributed to spatial heterogeneity and the unavoidable separation of hydrophobicity and moisture measurement points (since ethanol drops would affect moisture content). Many studies have reported low water contents corresponding to high hydrophobicity persistence and severity and *vice versa*, but defining a universal soil moisture 'switching' threshold has proved elusive. In field experiments in Portugal, Leighton-Boyce (2002) 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).~~

~~5.1.3 Soil moisture~~

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

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

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

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

~~Saturation was also 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, Latron and Gallart (2007), found a linear relationship between saturated area extent and baseflow discharge, with water table height also being important in explaining the saturation pattern. The locations and sizes of the wettest areas in the *Ribeira dos Covões* catchment varied temporally, a feature also noted in~~

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

~~5.1.4 Infiltration capacity~~

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

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

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

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

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

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

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

~~Differences in temporal variability of soil hydrological properties between landscape units led to spatial fluctuation in overland flow sources and sinks. Following dry periods (30/09/2010 and 13/06/2010), soil dryness was widespread and hydrophobicity was dominant and most severe mainly in woodland and agricultural-limestone areas, because of vegetation density and type. Drought-induced hydrophobicity promoted very low matrix infiltration capacity, making these landscape units susceptible to infiltration-excess overland flow generation in succeeding rainstorms. In urban and agricultural-sandstone areas, greater infiltration capacity under the same conditions (Figure 10) made these areas overland flow sinks. In woodland and agricultural-limestone areas, however, prolonged or repeated rainfall events led to partial switching, reductions in hydrophobicity severity and spatial extent, and enhancement of infiltration capacity. Hydrophobicity in eucalyptus~~eucalypt~~ stands is more resistant to break down, requiring longer and/or a greater~~

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

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

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

~~Spatial variability of soil properties *within* the same landscape unit, such as particle size and hydrophobicity, provides heterogeneous infiltration capacities (Figure 9). Soil spots with matrix infiltration capacity lower than rainfall intensity will lead to infiltration-excess overland flow, which may be infiltrated in surrounding soil spots with greater infiltration capacity. Only the few most permeable soil patches found in the landscape units could cope with a rainfall intensity of 5.4 mm h^{-1}, the mean hourly rainfall intensity of storm events ≥5mm recorded in the years 2010-2011. Not all the 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 wettest conditions, woodland provided sites of high infiltration capacity. The generally higher permeability of sandstone than limestone areas highlights the former's lower potential for infiltration-excess overland flow generation. 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.~~

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

~~hydrophobic soil matrix may be explained by preferential flow via macropores provided by, for example, roots, invertebrate activity and high concentrations of stones (e.g. Urbanek and Shakesby, 2009; Hardie et al., 2011), and is viewed as an important mechanism in both 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). Cracks in clay soils were observed in dry conditions during fieldwork in the catchment study.~~

5.2~~3~~ Implications for catchment runoff delivery and land management

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

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

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

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

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

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

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

The susceptibility of urban core areas located in topographic lows (Figure 2b) to ~~saturation-excess~~saturation overland flow and stream flooding may represent a real flood hazard for the inhabitants, particularly considering the ~~recent~~ scale of recent urban consolidation in the *Ribeir~~o~~a dos Cov~~o~~ões catchment*. This risk may be enhanced by 1) additional overland flow resulting from greater connectivity with upslope areas subject to soil moisture increase and water table rise, and 2) the rapid transfer of most overland flow from upslope impermeable surfaces directly into the stream via the urban drainage system. These may be particularly important in larger storm events, considering the generally low soil permeability across the catchment. ~~Based on~~According to interviews with older citizens ~~interviews~~, f~~F~~looding events ~~hazards~~ were already experienced ~~by older citizens which have reported flood events~~

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

Analyses of storm hydrographs of the outlet stream (results not shown) suggest that the actual landscape mosaic of *Ribeira dos Covões* catchment, comprising extensive woodland areas and large urban areas near the catchment outlet, together with numerous smaller urban areas mainly along ridges ~~upslope with minor~~ and dispersed agricultural fields (Figure 2b), may be sufficient to promote discontinuities to the infiltration-excess overland flow generated by soil hydrophobicity. Thus, in dry settings, rainstorms of 2.8 mm (average) and 14.4 mm (large), recorded on 6th August and 1st September 2011, promoted runoff coefficients for the Ribeir~~o~~a dos Cov~~o~~ões stream of only 5% and 2% respectively and~~. These rainfall events resulted in~~ peak streamflows of only 0.041 mm h^{-1} and 0.036 mm h^{-1}, compared~~associated~~ with maximum 5-minute rainfall intensities of 2.4 mm h^{-1} and 9.6 mm h^{-1} respectively. Thus, hydrophobicity over the catchment does not translate into catchment-scale overland flow, presumably due to infiltration into sinks ~~and interception~~ downslope. In wet conditions, however, enhanced soil moisture levels seem to increase flow connectivity over the catchment. Thus rainstorms of 2.8 mm and ~~14~~15.0~~4~~ mm registered on 11th February and 28th March 2011, led to 10% and 9% storm runoff coefficients and peak flows of 0.079 and 0.370 mm h^{-1}, compared with maximum rainfall intensities of 9.6 mm h^{-1} in both cases. Although lag times from peak rainfall to peak streamflow are short, ranging between 25 and 35 minutes, and probably a direct result of urban surface runoff and the urban drainage system, the overriding feature is the small size of the storm runoff coefficients both ~~in~~ during dry and wet times of the year, which shows how little of the rain falling on the peri-urban mosaic actually reaches the stream network. This may reflect in part ~~of~~ the ridge location of much of the urban expansion to date and in part a rather high proportion of infiltration into urban soil within the urban units and adjacent landscape units.

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

~~5~~6 Conclusions

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

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

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

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

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

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

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

~~6~~7 Acknowledgements

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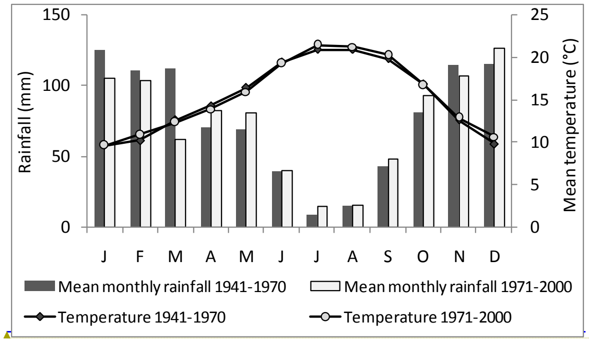
Figures



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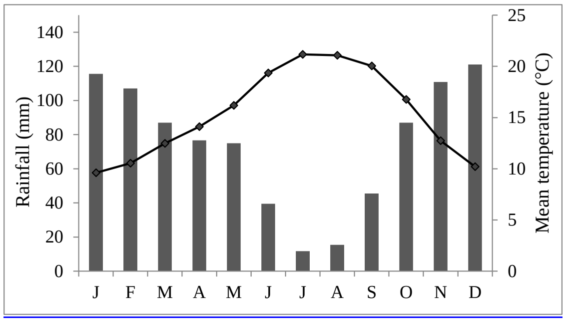
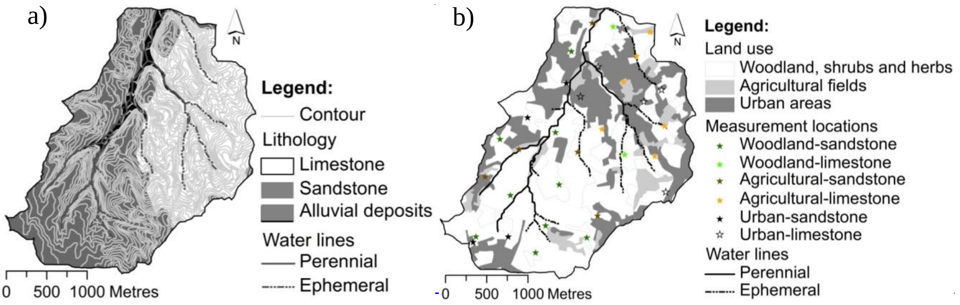


Figure 1 – Average monthly rainfall and temperature at Coimbra (Bencanta weather station) for the periods 1941~~-1970 and 1971~~-2000 (INMG, 1941-2000).



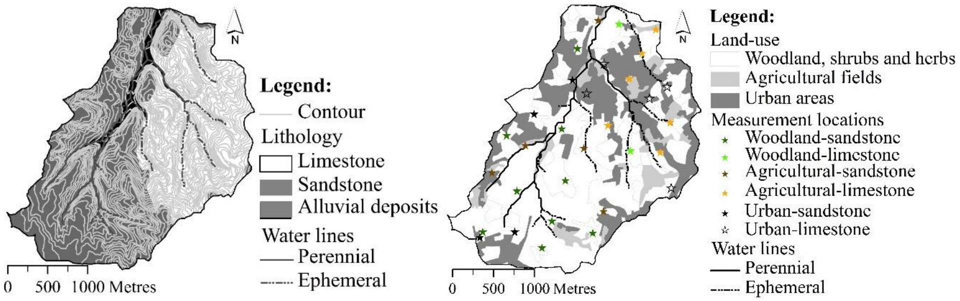
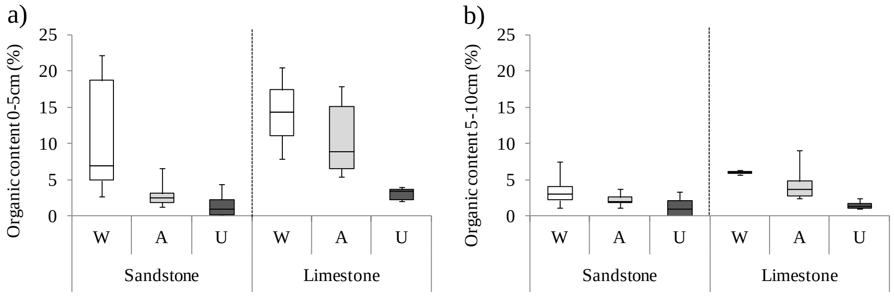


Figure 2 – *Ribeira dos Covões* catchment: (a) topography, lithology and streams; (b) land-use in 2009 and location of the study sites.



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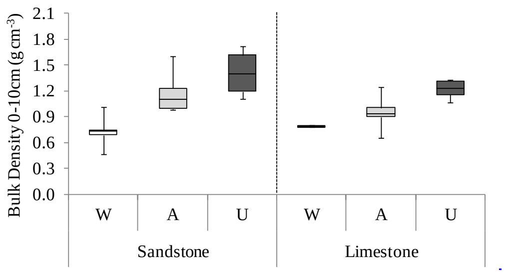
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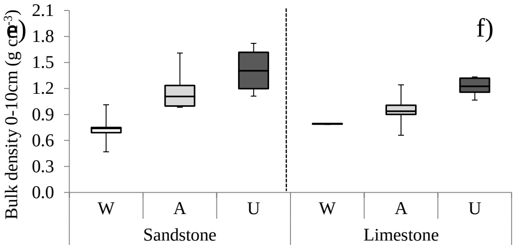
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Bulk density 0-10cm (g cm^{-3})
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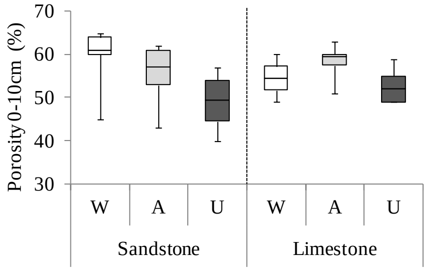
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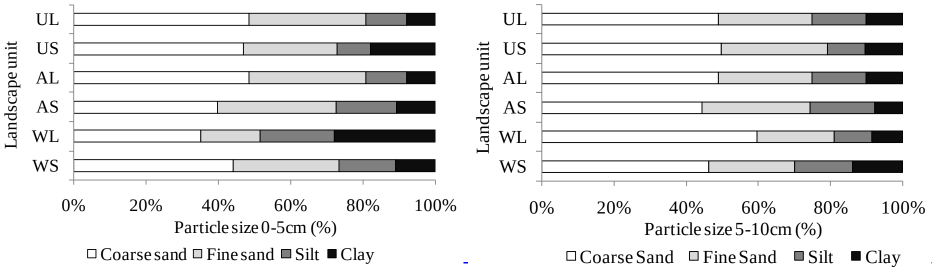
Sandstone
Limestone



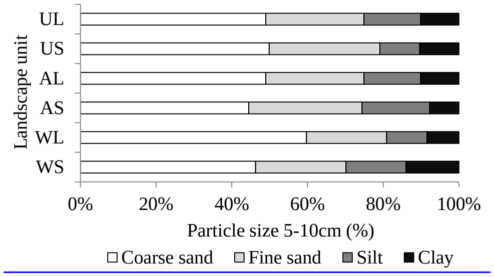


Figure 3 – Soil properties in different landscape units: a) organic matter content at the surface (0-5cm) and b) subsurface (5-10cm), c) bulk density (0-10cm), d) porosity (0-10cm), e) particle size distribution of surface (0-5cm), and f) subsurface soil (5-10cm) (W: woodland, A: agricultural, U: urban,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

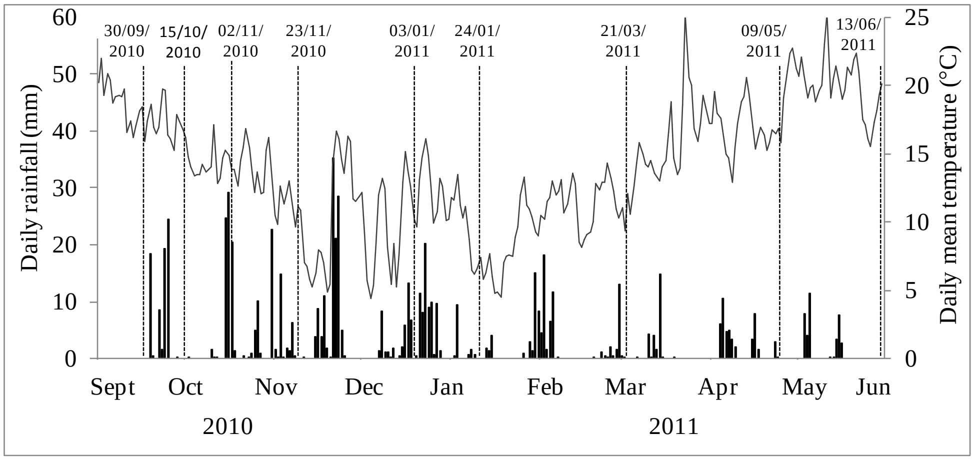


Figure 4 – Daily rainfall and mean daily temperature during the monitoring period September 2010 – May 2011 with dates of field measurements.

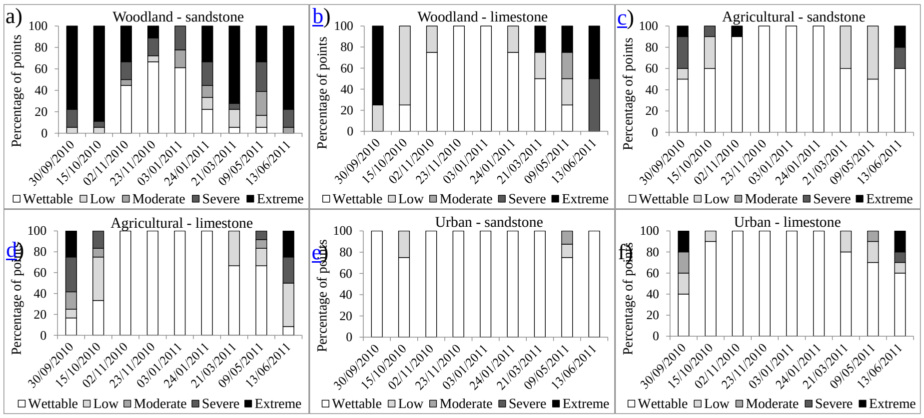
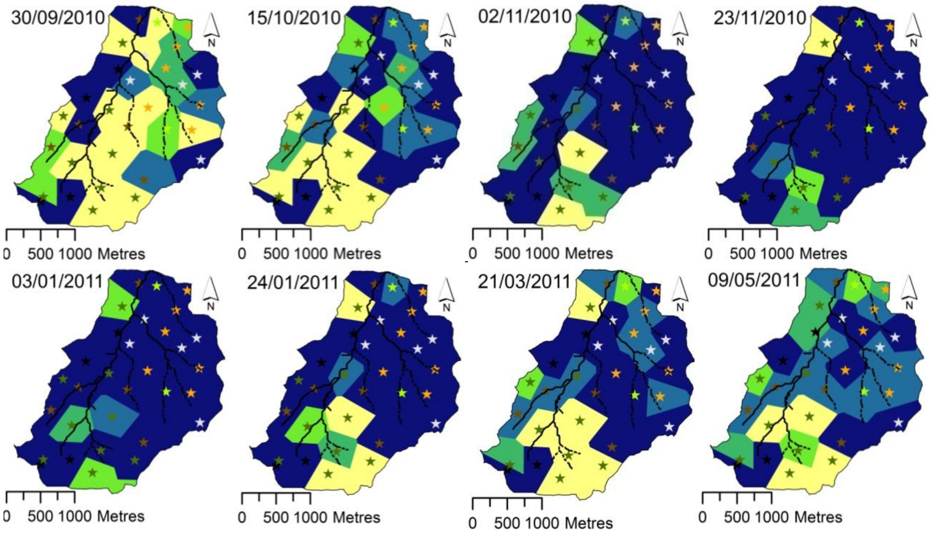


Figure 5 – Temporal variability of surface hydrophobicity for individual landscape units: a) woodland-sandstone, b) woodland-limestone, c) agricultural-sandstone, d) agricultural-limestone, e) urban-sandstone, f) urban-limestone.



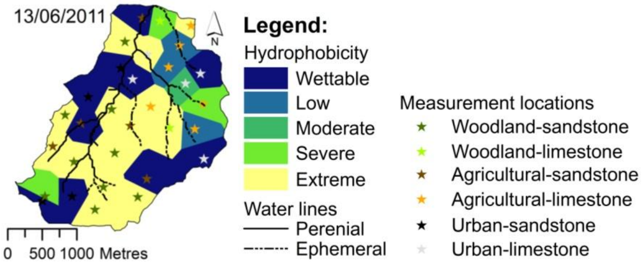


Figure 6 – Spatial variation of median soil hydrophobicity at the measurement dates, based on the Thiessen polygon method.

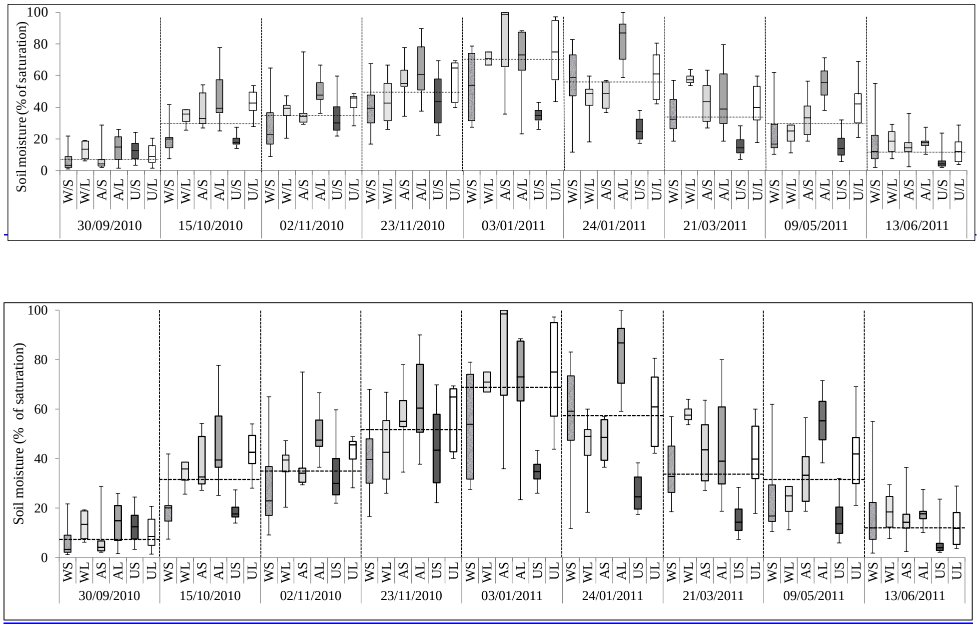


Figure 7 – Box-plots of soil moisture content for the different landscape units for the study period (W: woodland, A: agricultural, U: urban, S: sandstone, L: limestone). Horizontal dashed lines represent median soil moistures across the catchment, for the 9 measurement dates.

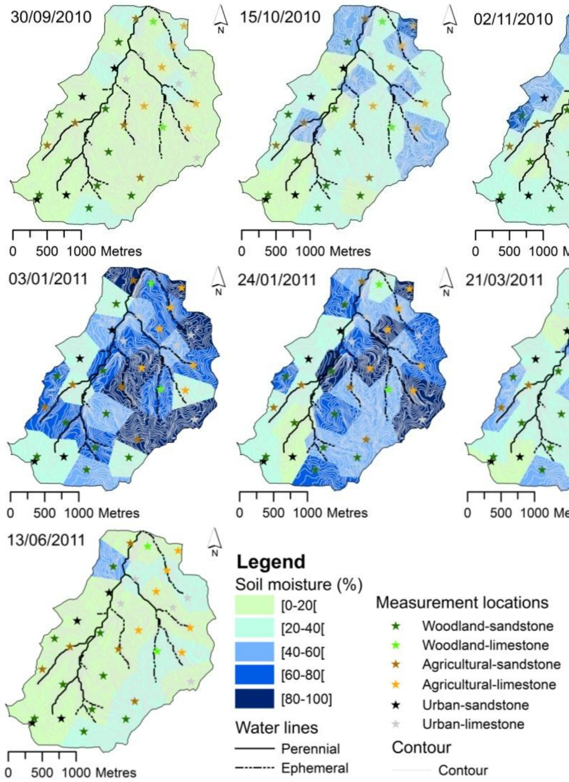


Figure 8 – Spatial distribution in median soil moisture content for each the measurement date, using the Thiessen polygon method.

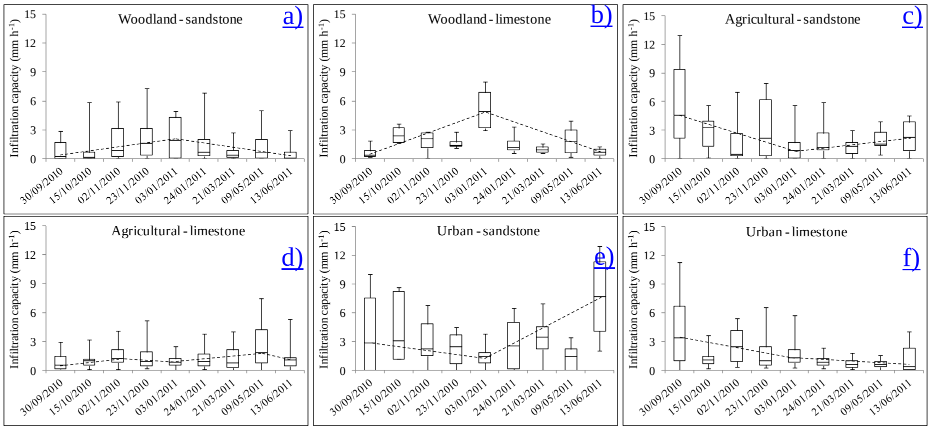


Figure 9 – Box plots of temporal variability of matrix soil infiltration capacity for each landscape unit. Dashed lines represent median temporal variability through the whole study period: a) woodland-sandstone, b) woodland-limestone, c) agricultural-sandstone, d) agricultural-limestone, e) urban-sandstone,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

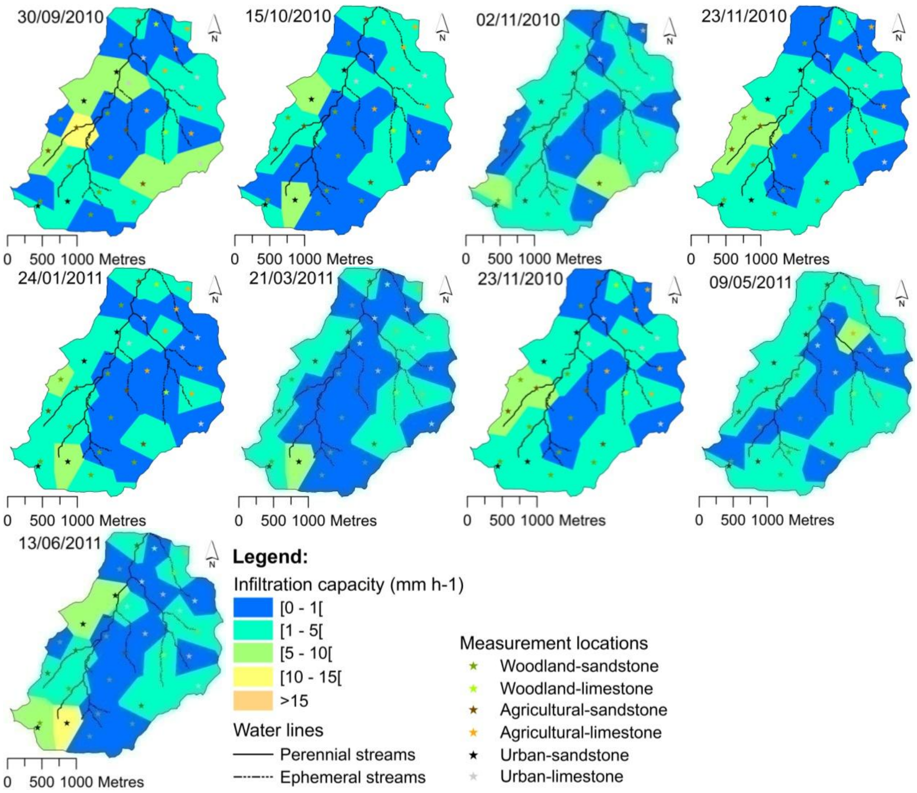


Figure 10 - Spatial variation in median matrix soil infiltration capacity at each measurement date~~s~~, considering Thiessen Polygon method for data distribution.

Tables

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 (ºC)
		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~~28~~	0.2	3.1	12.5	47.2	16.3
13/06/2011	37.0	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

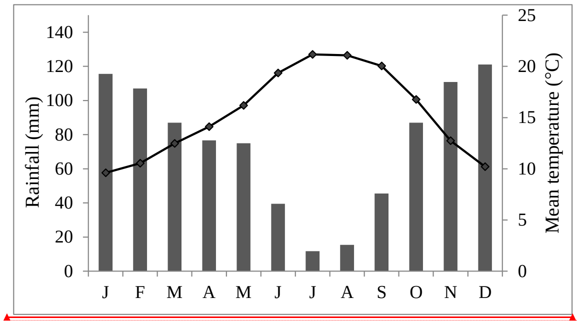


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Figure 1 – Average monthly rainfall and temperature at Coimbra (Bencanta weather station), calculated from data regarding to ~~for~~ the period~~s~~ 1941~~-1970 and 1971~~-2000 (INMG, 1941-2000).

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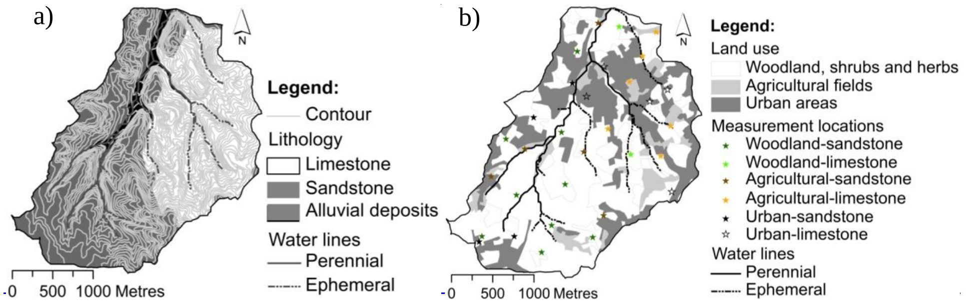

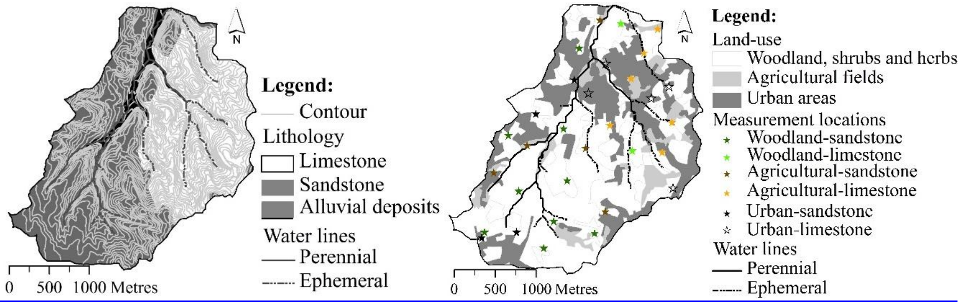

Figure 2 – *Ribeira dos Covões* catchment: (a) topography, lithology and streams; (b) land-use in 2009 and location of the study sites.

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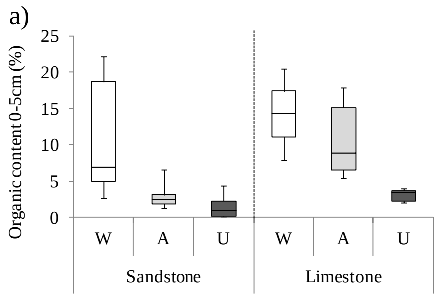
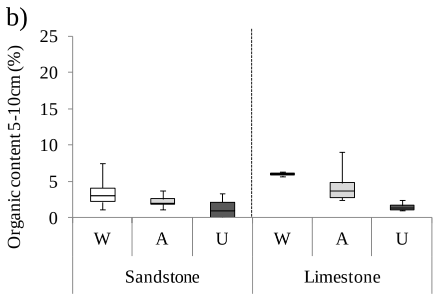
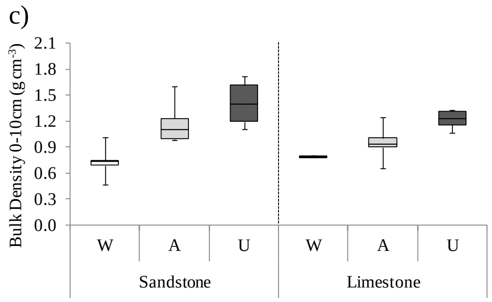
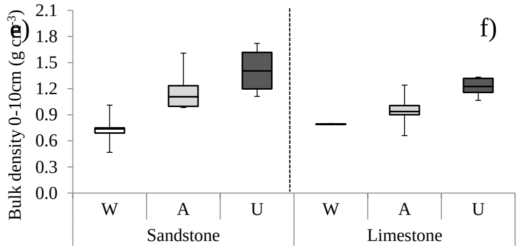
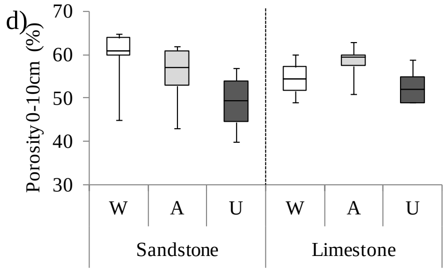

a)
Organic content 0-5cm (%)
25
20
15
10
5
0
W
A
U
W
A
U
Sandstone
Limestone


b)
Organic content 5-10cm (%)
25
20
15
10
5
0
W
A
U
W
A
U
Sandstone
Limestone


c)
Bulk Density 0-10cm (g cm-3)
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.0
W
A
U
W
A
U
Sandstone
Limestone


e)
f)
Bulk density 0-10cm (g cm-3)
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.0
W
A
U
W
A
U
Sandstone
Limestone


d)
Porosity 0-10cm (%)
70
60
50
40
30
W
A
U
W
A
U
Sandstone
Limestone

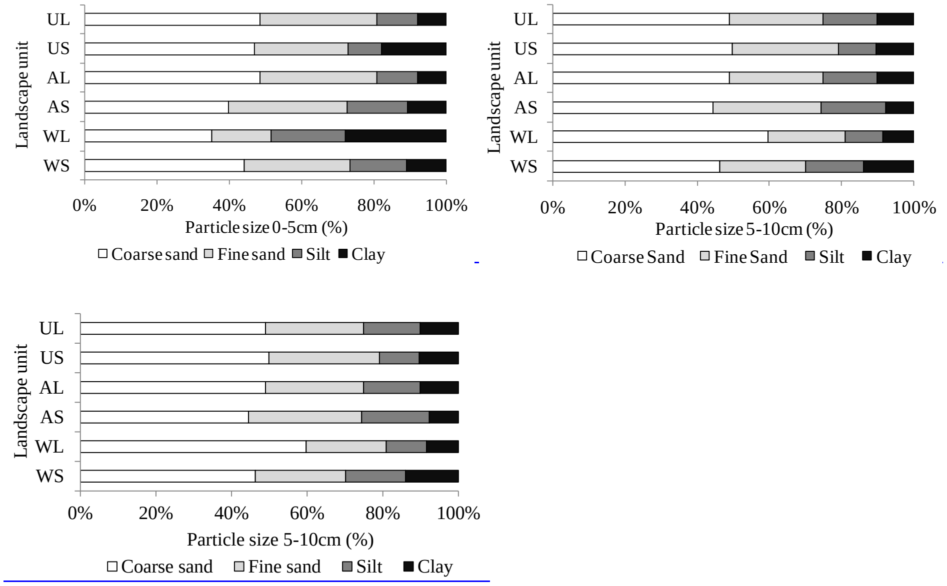


Figure 3 – Soil properties in different landscape units: a) organic matter content at the surface (0-5cm) and b) subsurface (5-10cm), c) bulk density (0-10cm), d) porosity (0-10cm), e) particle size distribution of surface (0-5cm), and f) subsurface soil (5-10cm) (W: woodland, A: agricultural, U: urban,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

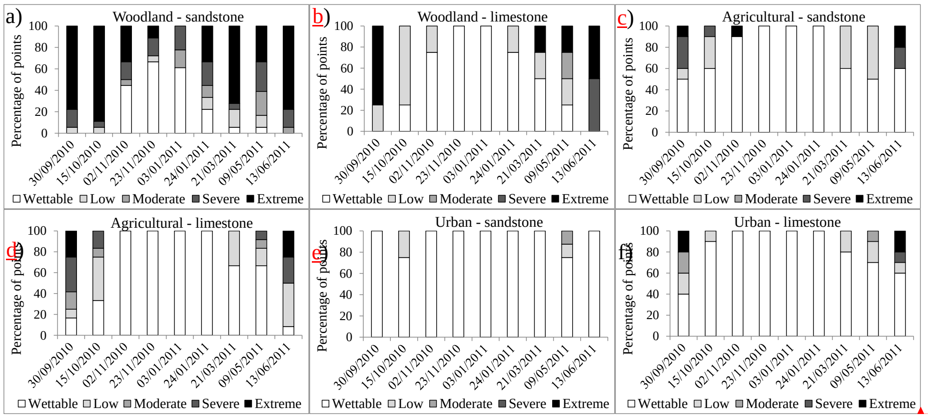


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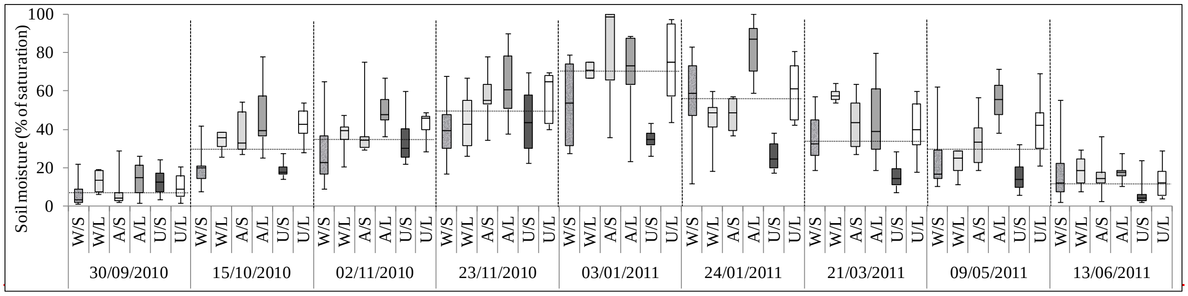
Figure 5 – Temporal variability of surface hydrophobicity for individual landscape units: a) woodland-sandstone, b) woodland-limestone, c) agricultural-sandstone, d) agricultural-limestone, e) urban-sandstone, f) urban-limestone.



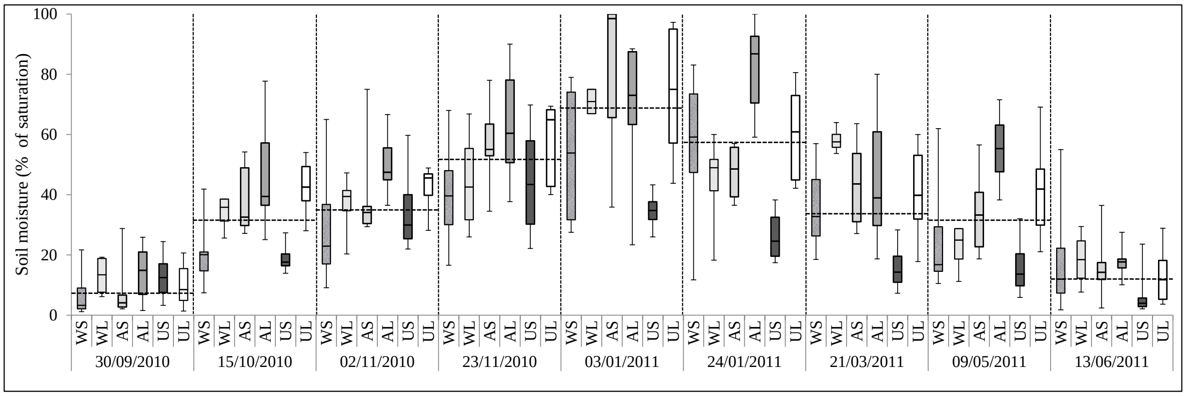
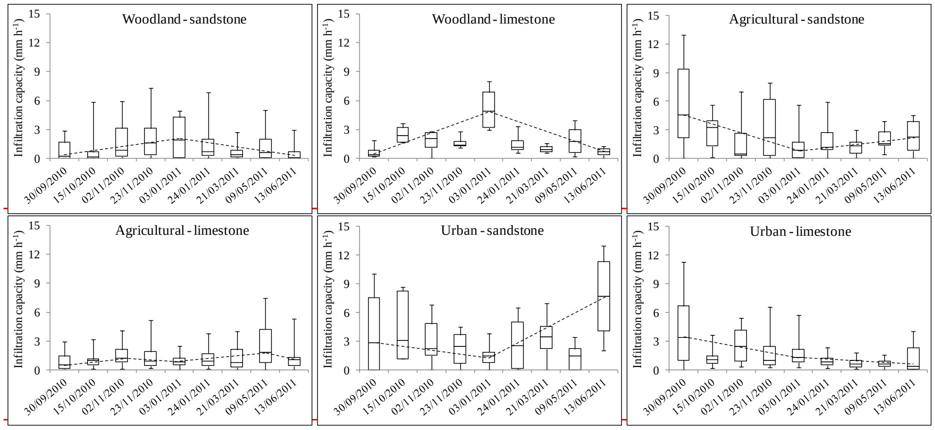


Figure 7 – Box-plots of soil moisture content for the different landscape units for the study period (W: woodland, A: agricultural, U: urban, S: sandstone, L: limestone). Horizontal dashed lines represent median soil moistures across the catchment, for the 9 measurement dates.



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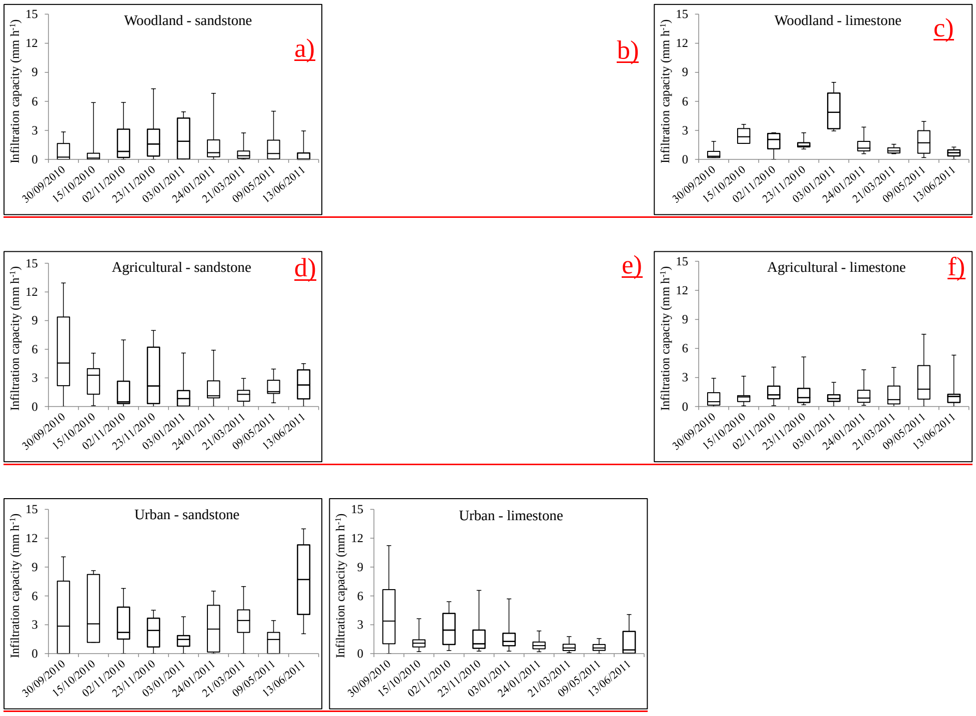

Figure 9 – Box plots of temporal variability of matrix soil infiltration capacity for each landscape unit. ~~Dashed lines represent median temporal variability through the whole study period~~a) woodland-sandstone, b) woodland-limestone, c) agricultural-sandstone, d) agricultural-limestone, e) urban-sandstone,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

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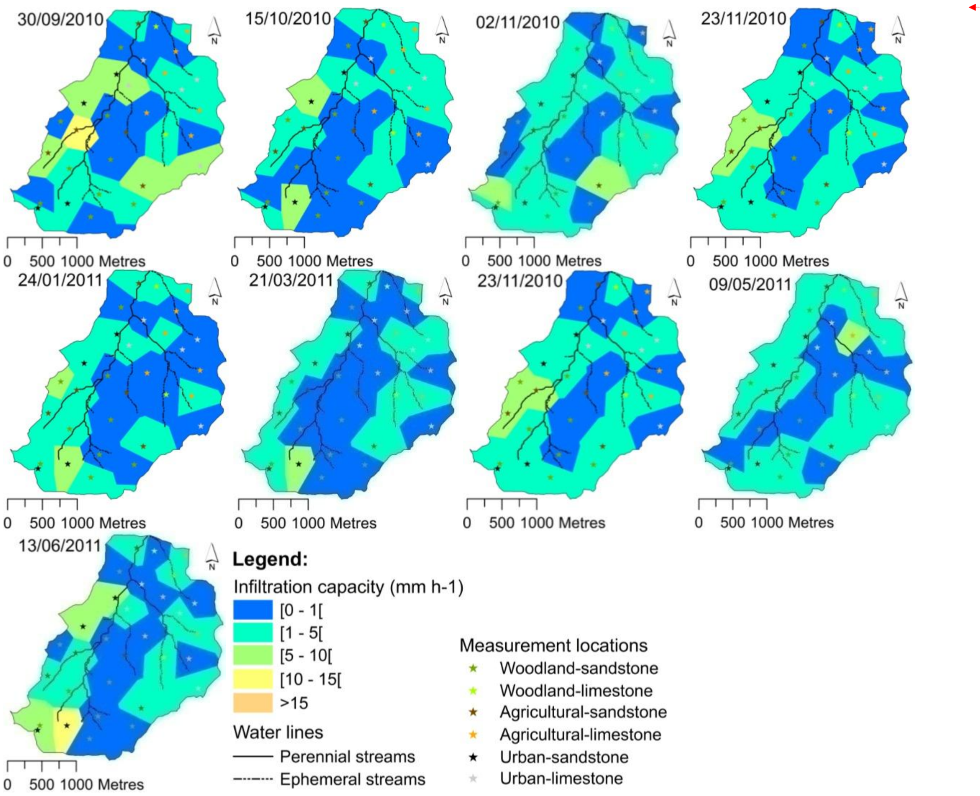

Figure 10 - Spatial variation in median matrix soil infiltration capacity at each measurement date~~s~~, using the Thiessen Polygon method.

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

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Measurement date	Total rainfall between measurements (mm)	Antecedent rainfall (mm)				Mean temperature during previous 5 days (ºC)
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