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

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SUMMARY

Forest hydrology has been widely investigated, but the impacts of different woodland types on hydrological processes within a peri-urban catchment mosaic are poorly understood. This paper investigates overland flow generation processes in three different types of woodland in a small (6.2 km^2) catchment in central Portugal that has undergone strong urban development over the past 50 years. A semi-natural oak stand and a sparse eucalyptus stand on partly abandoned peri-urban land and a dense eucalyptus plantation were each instrumented with three 16 m^2 runoff plots and 15 throughfall gauges, which were monitored at c. 1- to 2-week intervals over two hydrological years. In addition, surface soil moisture content (0–5 cm) and hydrophobicity (0–2 cm, 2–5 cm and 5–7 cm) were measured at the same time as overland flow and throughfall. Although all three woodland types produced relatively little overland flow (<3% of the incident rainfall overall), the dense eucalypt stand produced twice as much overland flow as the sparse eucalypt and oak woodland types. This contrast in overland flow can be attributed to infiltration-excess processes operating in storms following dry antecedent weather when severe hydrophobicity was widespread in the dense eucalypt plantation, whereas it was of moderate and low severity and less widespread in the sparse eucalypt and oak woodlands, respectively. In contrast, under wet conditions greater (albeit still small) percentages of overland flow were produced in oak woodland than in the two eucalypt plantations; this was probably linked to saturation-excess overland flow being generated more readily at the oak site as a result of its shallower soil. Differences in water retention in surface depressions affected overland flow generation and downslope flow transport. Implications of the seasonal differentials in overland flow generation between the three distinct woodland types for the hydrological response of peri-urban catchments are addressed.

1. Introduction

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

Forest hydrology has been widely documented, particularly with respect to some hydrological processes. Interception has been measured and modelled for many forest stands, indicating differences linked to distinct canopy architectures, woody matter, leaf characteristics and biomass (Muzylo et al., 2009; Rao et al., 2011). As a result of these factors (and climatic factors, notably rainstorm size distribution), throughfall varies greatly between forests, typically from 65% to 90% of precipitation, with stemflow generally varying from 0% to 15% (Herwitz and Levia, 1997;

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Crockford and Richardson, 2000; Wei et al., 2005). Differences in these processes can affect soil moisture distribution (Savva et al., 2013; He et al., 2014) and overland flow generation. Partly because overland flow is often considered a minor component of forest hydrology (Eisenbies et al., 2007; Gomi et al., 2008), few studies have focused on differences in overland flow between different forest types, and in particular between unmanaged, often abandoned woodland types affected by peri-urbanization process and pre-existing managed forest plantations.

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

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

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

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

2. Study area

The study was carried out in the peri-urban *Ribeira dos Covões* catchment (8°27′W, 40°13′N), located 3 km NW of Coimbra, the largest city in central Portugal. The catchment (Fig. 1) is 6.2 km^2 in area, is aligned S–N and ranges in altitude from 34 to 205 m a.s.l. The area has a Mediterranean climate, with a mean annual temperature of 15 °C and an average annual rainfall of 892 mm over the period 1941–2000 recorded at Coimbra-Bencanta (national meteorological weather station 12G/02UG), sited 0.5 km north of the study catchment. A dry and hot season occurs from June to August (8% of annual rainfall), whereas the rainiest period is from November to March (61% of annual rainfall). Rainfall events are mostly small, with 83% of daily rainfalls in 2001–13 at Coimbra-Bencanta being <10 mm. Annual maximum daily rainfalls in 2001–13 ranged from 20 mm to 102 mm. The catchment is underlain by sandstone (57%) and limestone (43%). Soils developed on sandstone are classified as Fluvisols and Podsols, following the WRB (2006) classification, and are generally deep (>3 m), while the Leptic Cambisols found on limestone slopes are typically shallow (<0.4 m) (Pato, 2007).

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

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