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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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SUMMARY

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 modeling flow connectivity and catchment hydrologic response. Such information is important for land managers in order to improve urban planning to minimize flood risk.

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 surface and 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

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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., 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 modeling 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 15 °C, 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 (Fig. 1). The main watercourse is perennial, supplied by several springs, and there are several smaller ephemeral tributaries (Fig. 2). The geology (Fig. 2a) comprises Jurassic dolomitic and marly limestone in the east (49% of the catchment area), and

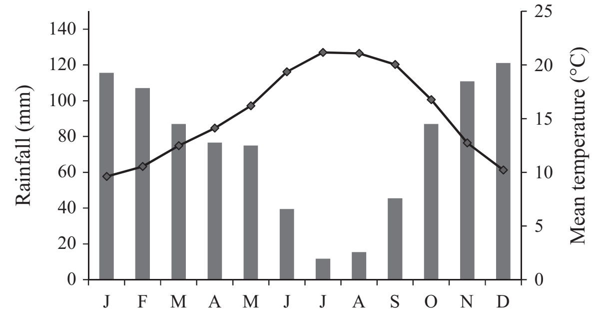

Fig. 1. Average monthly rainfall and temperature at Coimbra (Bencanta weather station), calculated from data regarding to the period 1941–2000 (INMG, 1941–2000).

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 (>3 m) Cambisols and Podzols (Tavares et al., 2012). Only on steeper slopes in the northwest is soil depth less than 40 cm. Altitude ranges from 29 m to 201 m. The average slope is 9°, but a few slopes reach up to 46°.

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 (Fig. 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” (Fig. 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