URBAN IMPACT ON CATCHMENT HYDROLOGY: FIRST RESULTS OF A PORTUGUESE CASE STUDY

Carla S.S. Ferreira[1,2*]; Daniel Soares[2]; António J.D. Ferreira[2]; Tammo S. Steenhuis[3]; João L.M.P. de Lima[4]; Celeste O.A. Coelho[1]

[1] Centre for Environmental and Marine Studies (CESAM), Department of Environment and Planning, University of Aveiro, Aveiro, Portugal

[2] Research Centre on Natural Resources, Environment and Society (CERNAS), Coimbra Agrarian Technical School, Bencanta, Coimbra, Portugal

[3] Department of Biological and Environmental Engineering, Cornell University, New York, USA

[4] Institute for Marine Research (IMAR), Marine and Environmental Research Centre, Department of Civil Engineering of the University of Coimbra, Coimbra, Portugal

*Email: cferreira@esac.pt

ABSTRACT

Land use changes and impermeable surface areas expansion alters the hydrological cycle. This paper presents the methodology and the first results of a study to assess the impact of urbanization process on the hydrological regime of a small Mediterranean catchment (6 km^2), *Ribeira dos Covões*, located in Portugal. The study uses a combined approach of field survey and hydrological monitoring to assess spatiotemporal hydrological dynamics. A monitoring network, integrating a weather station and eleven water level recorders, provides information on the sub-catchments's hydrological response to rainfall considering different geology, soil characteristics, land-use and urbanization intensity, and their contribution to the catchment outlet. In addition, six 16m^2 bounded plots are used to obtain the rainfall-runoff relationship of the forested areas. Infiltration experiments have been performed for spatial and temporal evaluation of the soil catchment. The results indicate distinct spatial and temporal variations in hydrological processes and different responses according with geology. Despite the low average runoff coefficient of the catchment (smaller than 10%), the streamflow increases quickly during the rainfall events, exhibiting a high susceptibility of the study site to flash floods.

Key words: urbanization, catchment hydrology, rainfall-runoff relationship.

1. INTRODUCTION

Population growth and the increase of socio-economic welfare experienced over the last decades led to a pervasive urbanization global trend (Duh *et al.*, 2008). Nearly half of the world's population lives in urban areas, and that percentage is expected to increase to 60% by the year 2030 (Burns *et al.*, 2005). This population pressure on the environment implies changes to land use and to landscape patterns within catchments, altering the connectivity of water flows between different sub-catchments, with potential consequences for rainfall-runoff relationships, affecting local and regional water resources as well as flood hazards (e.g., Alig *et al.*, 2004; Huang *et al.*, 2008).

Several researchers refer that the creation of impervious surfaces, associated with the urbanization process, induces major modifications in the natural water balance and in the various phases of the hydrological cycle, such as: reduction in evapotranspiration, decrease water infiltration capacity, associated with soil compaction (Arthur-Hartranft *et al.*, 2003; Easton *et al.*, 2007), changes in soil moisture content (Easton *et al.*, 2007; Easton & Petrovic, 2008), increase of surface runoff in annual streamflow (Corbet *et al.*, 1997; Semadeni-Davies *et al.*, 2008; Wheater & Evans, 2009), and decrease of baseflow and groundwater recharge (Xiao & McPhearson, 2003; Llorens & Domingo, 2007; Semadeni-Davies *et al.*, 2008; Wheater & Evans, 2009).

These changes are reflected in higher peak runoff, larger runoff volumes, decreased lag times to peak flow and a decrease in mean residence time of streamflow (Niemczynowicz 1999, Blake *et al.*, 2003; Brun & Band, 2000; Goonetilleke *et al.*, 2004; Burns *et al.*, 2005; White & Greerb, 2006; Semadeni-Davies *et al.*, 2008; Haase, 2009), leading potentially to increasing flood peaks. These can be particularly dramatic in small urban catchments due to flash floods risk and the associated damages to human lives and to properties.

However, despite the profusion of works, the impacts of potential land use change on storm-runoff generation remain largely unknown (Ying *et al*., 2009), particularly in areas with a Mediterranean climate, and predicting urban floods continues to present difficulties. This paper presents the methodology and the first results of a study that is being carried out to better understand how urbanization affects hydrological processes and flash flood occurrence on a Mediterranean catchment.

2. METHODOLOGY

2.1 Study site

The study was performed in *Ribeira dos Covões* catchment located in the central region of Portugal, near Coimbra city centre (the main city in central Portugal) (Figure 1). This small catchment has an area of 620 ha, and is a tributary to Mondego river system.

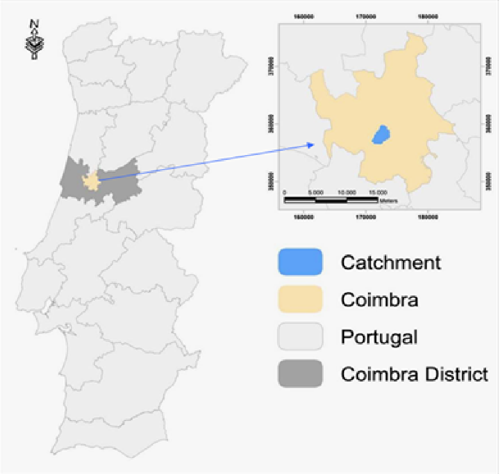

Figure 1 – *Ribeira dos Covões's* location.

2.1.1 Physiographic characteristics

The *Ribeira dos Covões* catchment presents an elongated shape, following the main stream development, which flows from South to North. The area is characterized by a humid Mediterranean climate, with an average annual temperature of 15ºC, an average annual rainfall of 980 mm/year with dry summers and wet winters.

Lithology is composed by Jurassic dolomitic and marl-limestone units on the eastern side, Cretaceous and Tertiary sandstones conglomerates and mudstones units on the west side, and on the surface we can find Plio-quaternary sandy-conglomerate and alluvial deposits . Soils are classified as Cambissol and Podzol by the FAO system (Pato, 2007).

Elevation of most of the catchment is between 65 and 150m with highest point at 205m. The average basin slope is 14%. Forty-five percent has slopes between 12-25%. The top and the bottom part of the catchment are relatively flat. Maximum slopes are in the range of 35%. The drainage density is 4 km km^{-2}, indicating a higher susceptibility to floods generation.

2.1.2 Population and land use

The study area experienced rapid land-use evolution in the past 50 years (Figure 2). Three periods of changes can be identified: i) 1958-1973 rural domain; ii) 1979 -1990 discontinuous urbanization and iii) 1990 - 2002 urban consolidation (Pato, 2007).

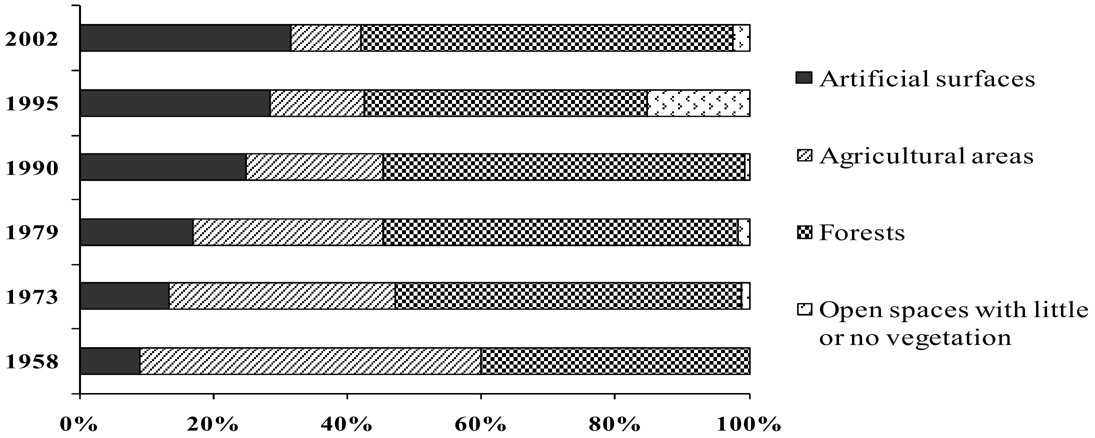

Figure 2 – Land use evolution between 1958 and 2002 in *Ribeira dos Covões* catchment (adapted from Pato, 2007).

Between 1958 and 2002 there were notably land use changes, with a significant increase of paved surfaces. This tendency is particularly notable after 1979, when houses construction increased. The forest areas increased slightly during the same period as a result of agriculture abandonment, leading to a 40.3% reduction of the agricultural area since 1958. The percentage of paved surfaces increased from 9.2% to 31.5 %, as a result of its proximity to the city of Coimbra. This situation has been indicated as one cause of a major flood in late 2006, underlining the need to study the impact of further urbanization on the catchment's hydrological processes.

Presently, 48% of the catchment is covered with forests, 25% is agricultural and the remaining 27% is urban land-use (Figure 3). Impermeable surfaces are expected to increase in a near future, as new urban areas that are currently being developed, particularly an industrial park that is under construction in the catchment headwater. Population living in the catchment in 2001 was estimated in 7000 inhabitants.

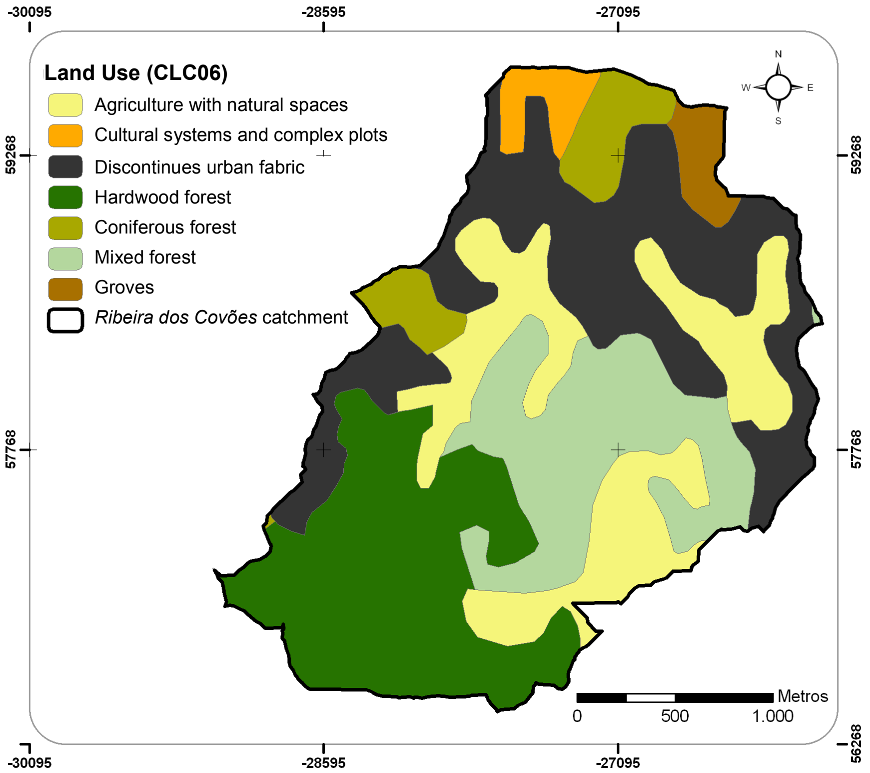

Figure 3 – Catchment land use (for the year 2006).

2.2 Experimental design

The study uses a combined approach of field survey and hydrological monitoring to assess spatiotemporal hydrological dynamics, focused at different scales (Figure 4).

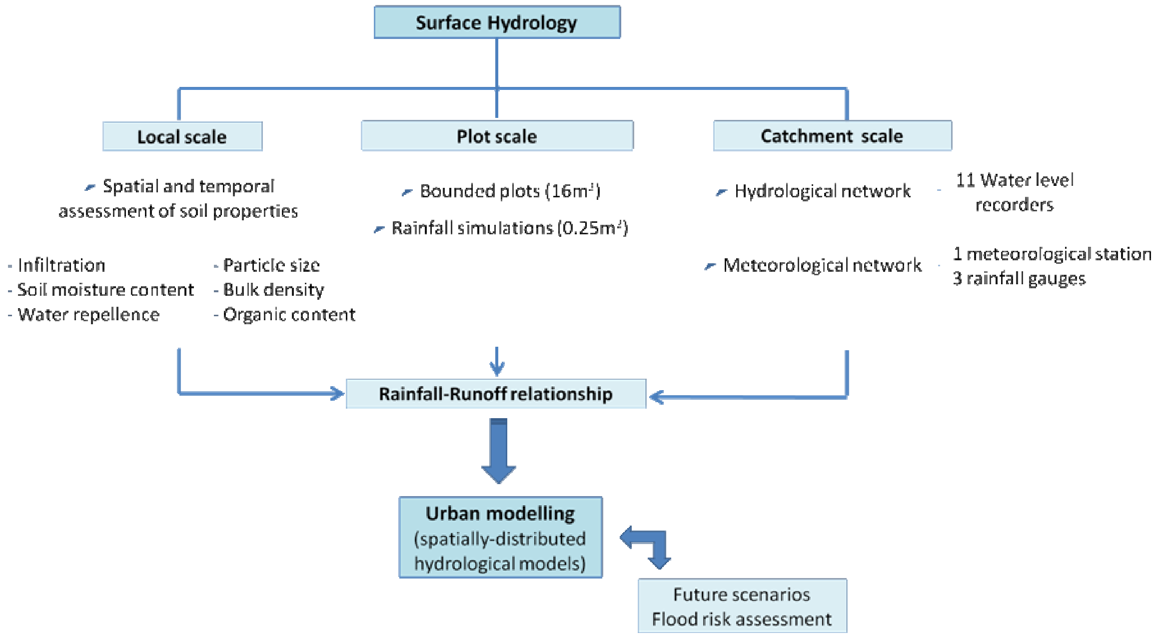

Figure 4 – Schematic representation of the methodology used.

The spatial and temporal variability of hydrological properties, such as water infiltration, soil moisture content and water repellence, have been monitored in the field to understand the most important runoff processes in non-urban areas of the catchment (Figure 5). Thirty one locations (eleven in forest areas, eleven in agriculture areas and nine in unpaved areas located in discontinuous urban fabric) were selected and since the summer 2010, for each site at approximate monthly time steps (eight times total) two infiltration experiments were carried out with a MiniDisk infiltrometer at 3.5cm suction. With each infiltration measurement both the gravimetric soil moisture content of the 5 cm surface soil and water repellence at 0cm, 2cm and 5cm depth using Molarity of Ethanol Drop method were determined. In addition, for each location, soil samples were collected in November 2010 at four depths (0-5cm, 5-10cm, 15-20cm and 45-50cm) for bulk density, particle size (Robinson pipette method) and organic content. Bulk density was determined with the core method and the organic matter content through carbon dioxide emission during 1200ºC samples combustion, in a Leco sc-144DR, Strohlein Instruments equipment.

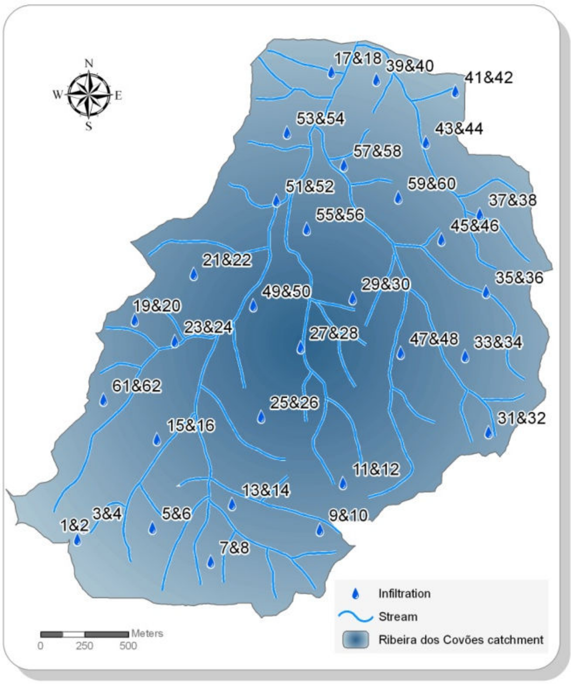

Figure 5 – Soil hydrological experiments location inside the catchment (the numbers represents code locations).

Due to the high variability at local scale, nine 16m^2 bounded plots were already installed to assess rainfall-runoff relationship under natural climatic conditions and have been monitored. The plots, in rectangular shape with a funnel form at the down slope end were bonded with metal plates and inserted between 5-10 cm soil depth. Considering the necessary area for these plots and the difficulty to obtain permission from the land owners for their installation, the plots were only installed in forest land uses. The plots were therefore installed in three different and representative forests areas (three plots per location): in an eucalyptus forest with a water repellent sandy loam soil; in a sandy loam soil but with higher shrub vegetation cover and lower trees cover; and in an oak forest in limestone area. At the down slope end, each plot was connected to a sediment Gerlach trough, by a continuous-recording device and to a barrel that accumulated all the runoff. In addition rainfall simulation experiments will be performed in a near future, in small plots (0.25) m^2 for a direct comparison of the rainfall-runoff relationship among different land-uses and different physiographical characteristics (local relief, aspect and gradient).

Besides the local and plot scales, the study also focuses on spatial and temporal variability of the hydrological processes at the sub-catchment level throughout hydrometric stations. This was performed, using a continuous recording monitoring network, including a weather station and a water level recorder, installed in the catchment outlet since 2005. Three additional rain gauges have been installed to assess spatial rainfall variability within the study catchment, and ten extra water level recorders (Figure 6) in later summer 2010 to monitor the streamflow generated in different sub-catchments. This hydrological network provides the data to assess the hydrological responses to rainfall and sub-catchments (characterized by different geology, soil characteristics, land-use and urbanization intensity) contribution to the outlet flow. For each rainfall event, parameters such as the time lag between rainfall and discharge, stream runoff coefficient and peak flow have been estimated with the available data.

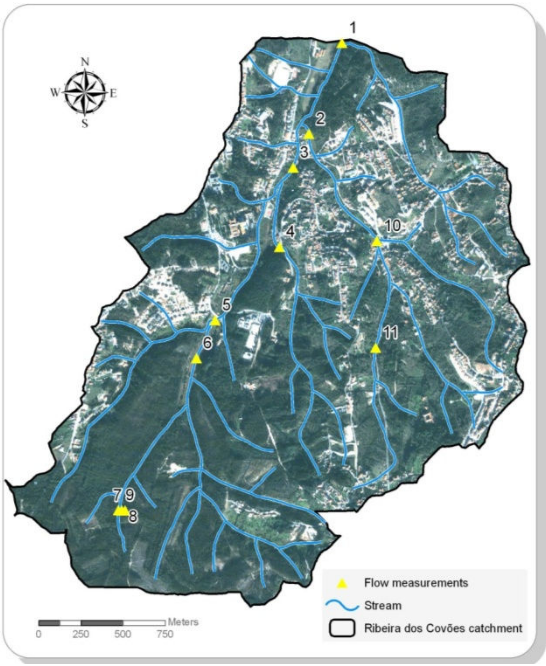

Figure 6 – Streamflow monitoring network plotted in an aerial photography (adapted from Google Earth map, 2006).

The meteorological network provides spatial and temporal data on basin-scale rainfall, while the hydrological network, together with the plot-scale data will provide the data for the assessment of hydrological response to rainfall. The existing urban drainage network study is under way, in collaboration with local water authorities, and will be considered to investigate the urban impact on catchment hydrological processes.

The information gathered will be used to provide the input data to feed, parameterize, calibrate, as well as validate a physically based and spatially distributed hydrological model, to study the effects of land-use changes due to urban growth. This methodology will be used to assess the impact of urbanization increasing and the impact of its location inside the catchment in flash flood response. It will be also used to simulate a number of planning strategies designed to mitigate flash flood impact.

3. FIRST FINDINGS AND DISCUSSION

3.1 Local scale

The eight infiltration monitoring campaigns were carried out along the time, mainly immediately after different rainfall events and, in the first two campaigns, after some rainless days (the 30-09-2010 campaign was carried out after the dry summer) (Figure 7).

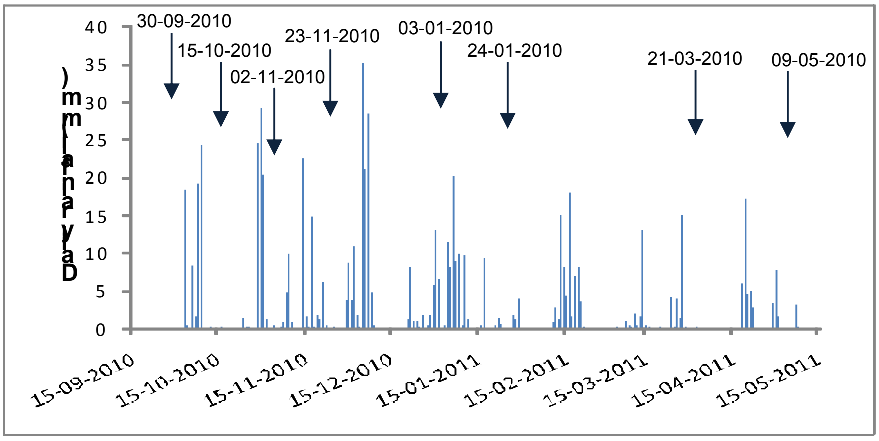

Figure 7 – Rainfall time series with dates of infiltration experiments.

The rainfall patterns between monitoring campaigns have a direct impact on soil moisture content (Figure 8). All the land uses considered for the study presented the same moisture content variability with the time, with lower values after the summer, increasing during the winter season, characterized by several rainfall events and lower temperatures, and reducing at the end of the winter with lower rainfall and higher temperatures (not presented in this paper).

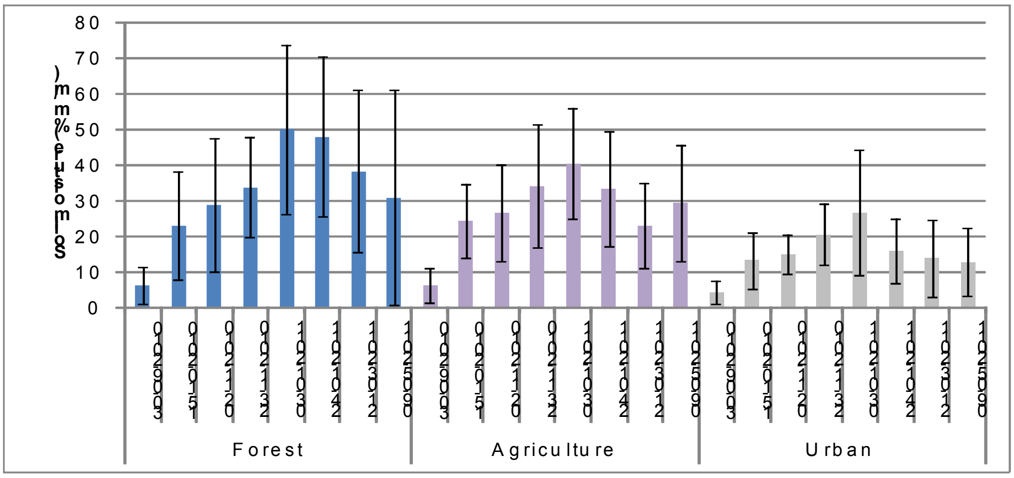

Figure 8 – Gravimetric soil moisture content registered during monitoring campaigns at 0-5cm depth.

In general, forest areas have a slightly higher soil moisture content than agricultural land use, which can be due to higher soil organic content (forest soils: 19.7±19.2%, agriculture: 7.2±5.7%, urban: 2.4±1.6%) and its capacity for water retention. The lower soil moisture content observed in discontinuous urban fabric can be a result of the soil compaction, indicated by the higher bulk density results (forest soils: 0.8±0.3 g/cm^3, agriculture: 1.3±0.3 g/cm^3, urban: 1.5±0.3 g/cm^3). In fact, the soil moisture content results registered in four monitoring campaigns (15-10-2010, 02-11-2010, 23-11-2010 and 24-01-2010) were statistically correlated with soil organic content (positive correlation) and bulk density (negative correlation) results.

During the first six monitoring campaigns, bulk density and soil organic content were also correlated with soil water repellence grades (negative and positive correlations, respectively) (Figure 9).

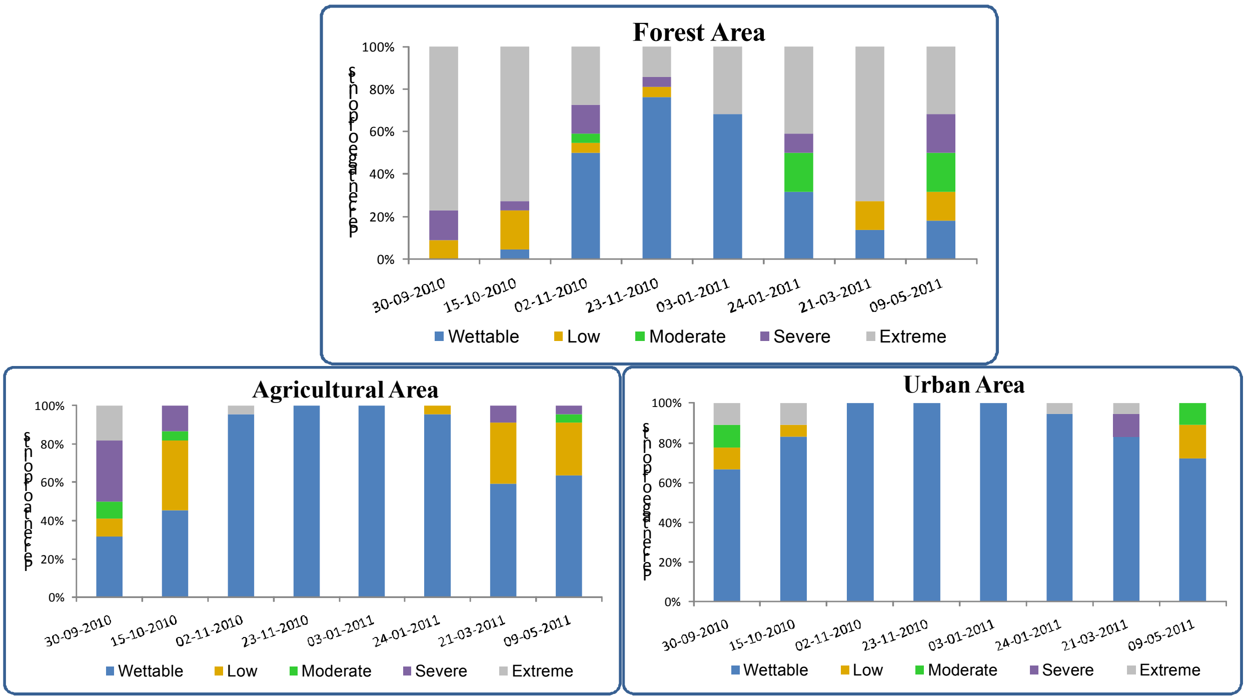

Figure 9 – Surface soil water repellence in the monitored land uses observed in the campaigns.

Despite the differences between land uses, the results exhibited the same response for water repellency: greater hydrophobicity during dry periods, especially after the summer, and becoming hydrophilic during wet periods. Forest areas had the greatest water repellence during dry periods. Moreover, repellence did not decrease with small rainfall events. In fact, between September and October campaigns there was 73 mm of rainfall and the soil was still extremely repellent. Several rainfall events are needed to allow the soil to get hydrophilic. Even then, after a few days without rain and with higher temperatures, the repellence behaviour reappears.

Agriculture areas presented some hydrophobicity that rapidly decreased during rainfall events (easier to break compared to the repellency in forest areas). In urban areas, the soil is mainly hydrophilic, also during dry periods. This can be associated to the lower organic content in the soil.

The results obtained during some monitoring campaigns showed a negative correlation between water repellency and infiltration capacity (Figure 10): 30-09-2010, 15-10-2011 and 21-03-2011 (campaigns performed after several days without rainfall and higher temperatures).

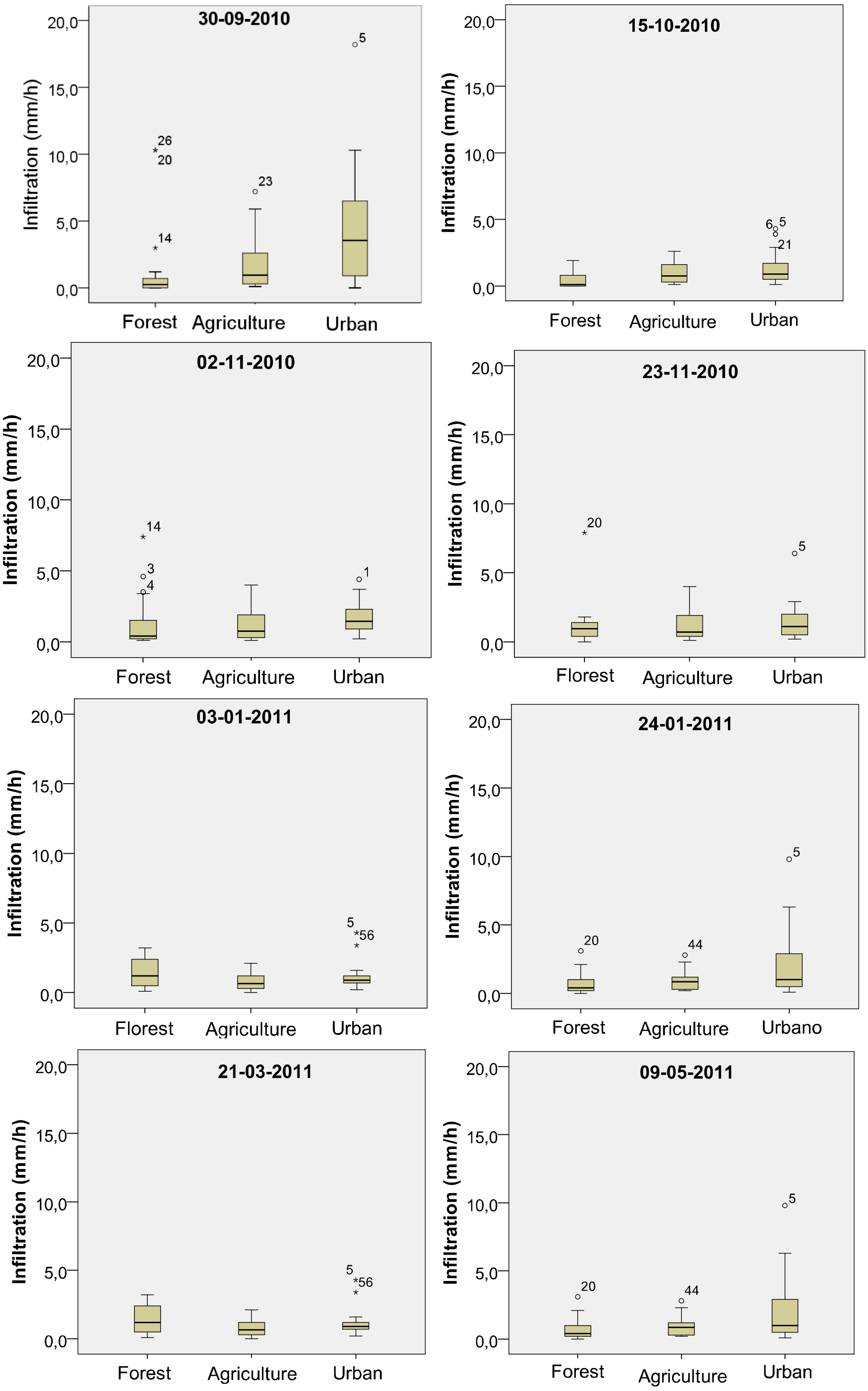

Figure 10 – Infiltration results obtained in different monitoring campaigns for different land uses (numbers in the pictures represent the locations references of outlier results).

The results indicate a high spatial and temporal variability on soil infiltration capacity within study area. Forest areas have the lowest infiltration capacity due to the water repellent nature of their soils especially during dry periods, as observed in 30/9/2010 and 3/1/2011. In the most highly repellent soils, no water infiltrated. However, during wet periods, water repellence decreased and water infiltration capacity increased, making these areas with higher infiltration comparing with agriculture and urban (see the results found during 03-01-2011 campaign), reaching 3.2 mmh^{-1}.

Agriculture areas presented little hydrophobicity after dry periods and it revealed a more constant infiltration capacity. In urban areas, where the soil is mainly hydrophilic, the infiltration capacity is high during dry periods (attaining 18 mmh^{-1}). Nevertheless, infiltration capacity declined associated with rainfall events and the soil moisture increase (during 03-01-2011 campaign, the average soil moisture content was 26.7% and the average infiltration was 1.3 mmh^{-1}).

The areas that produce runoff varies with the time of the year. During the summer when the soil is dry Hortonian overland flow ccurs on the water repellent (mainly forest) soils. On the other hand, during wet periods, hydrophobicity disappears and saturation overland flow occurs in low-lying areas where soils become saturated.

3.2 Bounded plots

A total of nine bounded plots were installed. In late December, three plots were installed in both the *IParque* and *Inês de Castro* forest areas. In February three more plots wer put in place in the *Aqueduto* forest. The biophysical characteristics of each forest area are distinct, but representative of the study site: 1) *IParque* is characterized by sandstone bedrock, sandy loam soil, extremely water repellent during dry periods; the plots are installed in a mixed forest (eucalyptus, pine and acacia) with a few shrub cover and considerable litter layer; the installed plots have distinct slopes (18º, 16º and 26º for *IPC*, *IPM* and *IPE*, respectively); 2) *Inês de Castro* is characterized by sandstone bedrock, loamy sand soil, strongly water repellent during dry periods; the plots are installed in steep slopes (26º - 28º) with a shrub dense vegetation cover and few eucalyptus trees; ; 3) *Aqueduto* forest is located in limestone bedrock, clay loam soil, mainly hydrophilic; the plots are installed in a dense oak forest with lower slope comparing with the previous plots (22º, 16º and 13º for *AQD*, *AQM* and *AQE*, respectively).

The runoff ratio (defined as the quotient of the amounts of runoff and rainfall) for various rainfall events in the forest plots are presented in Figure 11. Water repellency values are given in Figure 12.

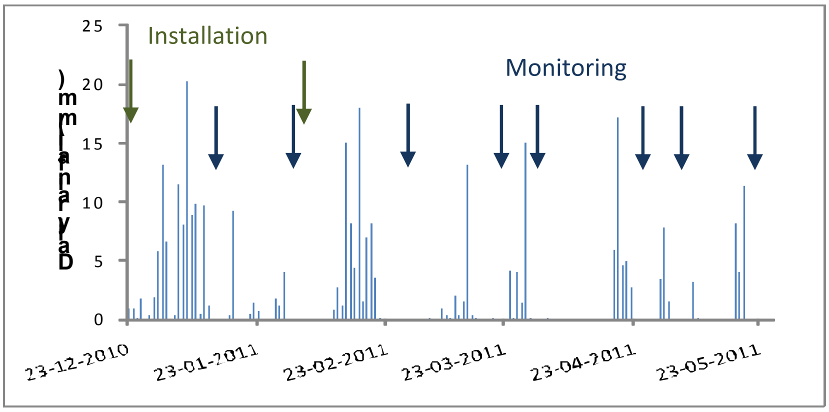

Figure 10 – Daily rainfall pattern during bounded plots monitoring.

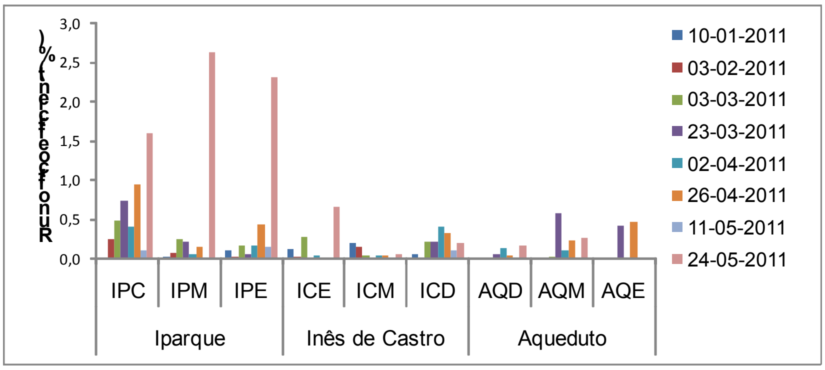

Figure 11 – Runoff coefficient registered during bounded plots monitoring.

Despite the short monitoring period, the preliminary results revealed a very low runoff coefficient (average values lower than 0.5%), which is concurrent with the infiltration experiments that pointed out high infiltration capacities during wet periods in forest areas. In general, plots installed in *IParque* had a slightly greater runoff coefficient compared with the other plots, but was still extremely small. The increasing runoff coefficient in *IParque* plots can be related to increasing soil moisture content and not to soil water repellency (Figure 12). *Aqueduto* forest plots initially did not have any runoff (0% runoff coefficient), as expected since they are in limestone area. The runoff coefficient in *Aqueduto* increases when water repellency increases (compare Figure 11 and 12).

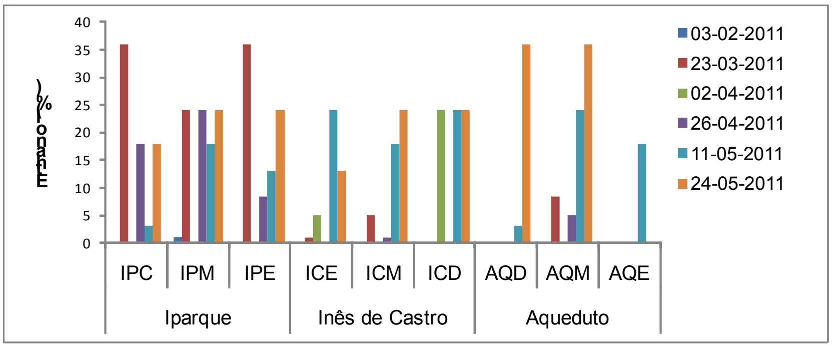

Figure 12 – Ethanol percentage used to evaluate soil water repellence around bounded plots (0%: wettable, 1%-5%: low, 8.5%-13%: moderate, 18%-24%: severe, 36%: extreme).

The low runoff coefficient exhibited at all forests areas indicates that forest can be used as infiltration zones for runoff water from urban areas. They can therefore be used as a “green” storm water management system when left intact. Or in other words, flood risks will increase greatly when a greater portion of the forest are paved over.

3.3 Catchment scale

The catchment shows a non homogeneous runoff pattern through time (Figure 13). The 2008 year was drier compared (total rainfall of 640mm) with 2009 and 2010 years (807 mm and 825.0 mm), and the streamflow was lower. The highest discharge of 2005 year was in May, at the end of the wet period. During 2009 year, the rainfall events were more concentrated in autumn and winter seasons comparing with the other year, and the highest discharge (400 L/s) was registered in November, after a daily rainfall of 68.6 mm. In 2010 year, the annual stream discharge was increased, with upper values during the drier summer comparing with the previous summer years, and with higher peak flow also observed during the more intense rainfall event, during the winter season.

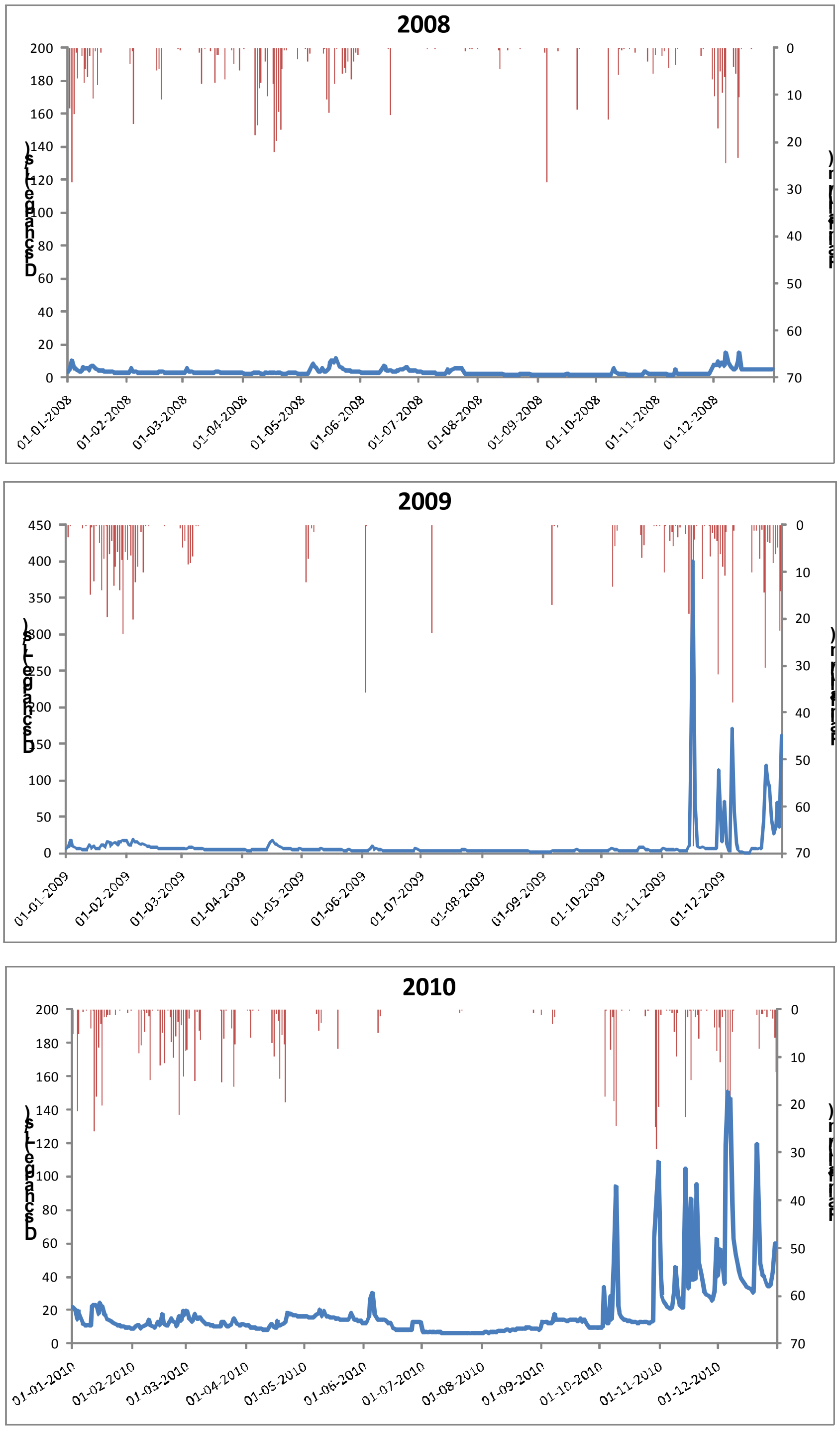

Figure 13 – Rainfall and stream flow discharge registered during 2008, 2009 and 2010 at the catchment outlet.

In general, runoff coefficients are less than 12% of total rainfall, which indicates that a major portion of the rain water is carried out via the subsurface from the catchment. Considering the urbanized area, runoff coefficients were expected to be greater, but can be explained by the limestone bedrock. However, runoff coefficients have been increasing during the monitored year: 2.5% in 2008, 6.4% in 2009 and 11.1% in 2010. The rise can be linked with rainfall pattern (also increased), but also with the urban areas expansion, considering the small difference in annual rainfall between 2009 and 2010.

In most cases, the runoff coefficients are greater during the dry periods. This is a consequence of soil water repellence, largely observed in the forest areas but also found in agriculture and non impervious urban areas (according with the local scale results presented above). Some springs identified in the sandstone area supply enough water during all the year to keep water flowing at the catchment outlet. On the other hand, according with the existent hydrological network, limestone area is only hydrologically active during rainfall events.

In general, despite the temporal variability in rainfall-runoff response, the catchment is characterized by a quick flow of streams (Figure 14 and 15).

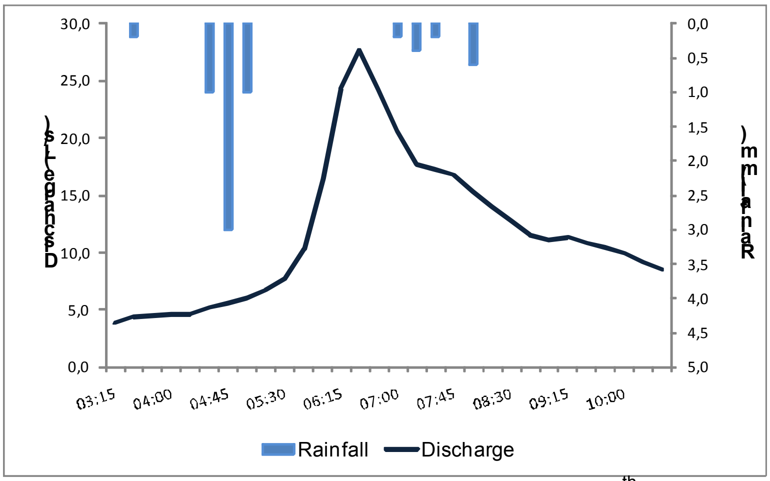

Figure 14 – Hydrograph generated with data from 15th May 2008.

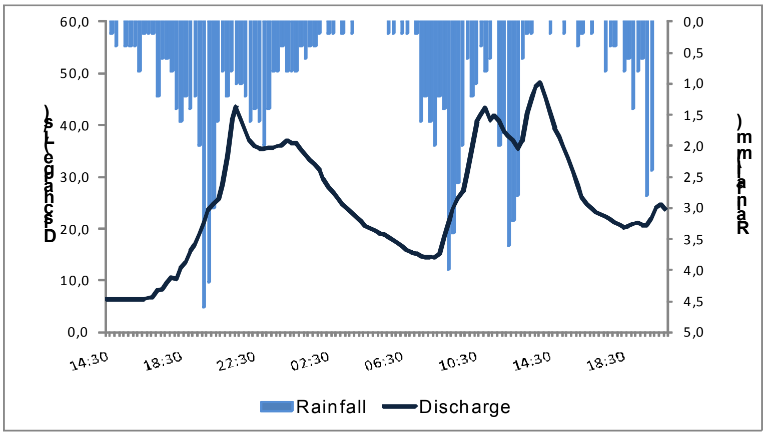

Figure 15 – Hydrograph generated with data from 14th and 15th May 2009.

According with hydrographs presented in Figures 14 and 15, two examples associated with higher rainfall events, the rainfall reaches the catchment outlet in less than one hour, pointing out the high susceptibility to flash floods.

4. CONCLUSIONS

The ultimate goal of the study is to gather the information to feed, parameterize, calibrate and validate a physical based and spatially distributed hydrological model, in order to simulate the impact of urbanization change on flash flood response and mitigation planning strategies. The first results of this study showed spatial and temporal variability in hydrological processes inside the *Ribeira dos Covões* catchment in infiltration capacity, which directly affect rainfall-runoff relationships. The abundance of different overland flow generating sources may increase and decrease depending on previous rainfall amounts and land use: during dry periods Hortonian overland flow is significant during rainstorms in the dry months and is generated on water repellent soils (mainly forest), while in wet periods saturation excess causes overland flow in flat and lower areas (mainly agriculture and open spaces located in discontinuous urban areas).

Despite the urbanization process, the catchment runoff coefficient is lower than 10% of rainfall, pointing out that land use discontinuities inside the study site promotes runoff infiltration into the soil on its way to the river. However, the runoff observed increase in last year's runoff can be a result of urban areas expansion. In fact, local older citizens, that lived their entire live in the study area, report higher pick flows during rainfall events observed in water lines located downstream recent urban areas. Considering the tendency for streamflow increase associated with urban areas expansion in near future, it is expected that flood risk will increase. For this reason, it is important to define and implement mitigation planning strategies that preserve or promote areas of water infiltration. The breaks in landscape connectivity, proven to be a major driving force in overland flow and runoff generation processes, can be efficiently performed by forest areas (according to bounded plots results obtained in this study).

ACKNOWLEDGEMENTS

The authors would like to thank the Soil and Fertility Laboratory of the Agrarian Technical School of Coimbra, particularly to Leonor Pato for the technical support. We are grateful to Manuel Nunes for the rainfall data, Célia Bento for the help with field work and Tânia Esteves for the help in preparing maps presented in Figures 3, 5 and 6.

REFERENCES

Alig, R.J.; Kline, J.D.; Lichtenstein, M., 2004. Urbanization on the US landscape: looking ahead in the 21st century. Landscape and Urban Planning, 69, 219–234.

Arthur-Hartranft, S.T., Carlson, T.N.; Clarke, K.C., 2003, Satellite and ground-based microclimate and hydrologic analyses coupled with a regional urban growth model. Remote Sens. Environ., 86, 385-400.

Blake, W.H., Walsh, R.P.D., Barnsley, M.J., Palmer, G., Dyrynda, P.; James, J.G., 2003. Heavy metal concentrations during storm events in a rehabilitated industrialized catchment. Hydrol. Processes, 17, 1923-1939.

Brun, S.E.; Band, L.E., 2000. Simulating runoff behaviour in an urbanizing watershed Computers. Environ. Urban Systems, 24, 5-22.

Burns, D.; Vitvar, T.; McDonnell, J.; Hassett, J.; Duncan, J.; Kendall, C., 2005. Effects of suburban development on runoff generation in the Croton River basin, New York, USA. Journal of Hydrology, 311, 266-281.

Corbetts, C.; Wahlb, M.; Portera, E.; Edwards, D.; Moised, C., 1997. Nonpoint source runoff modeling. A comparison of a forested watershed and an urban watershed on the South Carolina coast. Journal of Experimental Marine Biology and Ecology, 213, 133-149.

Duh, J.; Shandas, V.; Chang, H.; George, L., 2008. Rates of urbanisation and the resiliency of air and water quality. Science of the total environment, 400, 238-256.

Easton, Z.M.; Gérard-Marchant, P.; Walter, M.T.; Petrovic, A.M.; Steenhuis, T.S., 2007a. Identifying dissolved phosphorus source areas and predicting transport from an urban watershed using distributed hydrologic modeling. Water Resources Research, 43, 3413-3431.

Easton, Z.M.; Gérard-Marchant, P.; Walter, M.T.; Petrovic, A.M.; Steenhuis, T.S., 2007b. Hydrologic assessment of an urban variable source. Water Resources Research, 43, 3432-3450.

Goonetilleke, A.; Thomas, E.; Ginn, S.; Gilbert, D., 2005. Understanding the role of land use in urban stormwater quality management. Journal of Environmental Management, 74, 31–42.

Haase D., 2009. Effects of urbanisation on the water balance – A long-term trajectory. Environ. Impact. Asses. Rev., doi:10.1016/j.eiar.2009.01.002.

Huang, H.; Cheng, S.; Wen, J.; Lee, J., 2008. Effect of growing watershed imperviousness on hydrograph parameters and peak discharge. Hydrological Processes, 22, 2075–2085.

Llorens, P.; Domingo, F., 2007. Rainfall partitioning by vegetation under Mediterranean conditions. A review of studies in Europe. Journal of Hydrology, 335, 37– 54.

Niemczynowicz, J., 1999. Urban hydrology and water management – present and future challenges. Urban Water, 1, 1-14.

Pato, R. L. S., 2007, “Bacia Hidrográfica da Ribeira dos Covões. Variáveis biofísicas e evolução do uso do solo no período 1958-2002”, Dissertação apresentada para obtenção do grau de Mestre em Geociências (especialidade em Ambiente e Ordenamento do Território). Faculdade de Ciências e Tecnologia da Universidade de Coimbra, Coimbra, Portugual (in portuguese).

Semadeni-Davies, A.; Hernebring, C.; Svensson, G., 2008. The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: Combined sewer system. Journal of Hydrology, 350, 100–113.

White, M.D., Greerbb, K.A., 2006. The effects of watershed urbanization on the stream hydrology and riparian vegetation of Los Penasquitos Creek, California, Landscape and Urban Planning. 74, 125–138.

Wheater, H.; Evans, E., 2009. Land use, water management and future flood risk. Land Use Policy, 26S, S251–S264.

Xiao, Q.; McPherson, W.G., 2003. Rainfall interception by Santa Monica’s municipal urban forest. Urban Ecosystems, 6, 291-302.

Ying, C.; Youpeng, X.; Yixing, Y., 2009. Impacts of land use change scenarios on storm-runoff generation in Xitiaoxi basin, China, Quaternary International, doi: 10.1016/j.quaint.2008.12.014.