Assessment of surface hydrologic properties on a small urbanized mediterranean basin: experimental design and first results

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Messung oberflächenhydrologischer Eigenschaften eines städtischen, mediterranen Einzugsgebiets

Introduction

Population growth and the increase of socio-economic welfare experienced over the last decades have led to a worldwide tendency for population concentration in urban areas (Duh et al., 2008). This population pressure on the environment implies changes to land use and to landscape patterns within basins, altering the connectivity of water flows between different catchment compartments with impacts on local and regional water resources, which increase flood hazards (e.g., Alig et al., 2004; Huang et al., 2008).

Several researchers concluded that urbanization influences hydrology due to infiltration decline, decreased groundwater recharge and base flow and changes in surface runoff patterns (Semadeni-Davies et al., 2008; Easton et al., 2007; Wheater & Evans, 2009). These changes are reflected in higher peak flows, larger runoff volumes and decreased lag times to peak flow (Semadeni-Davies et al., 2008; Haase, 2009), leading to potentially dramatic effects on increasing flood peaks. However, despite the profusion of research, predicting urban floods continues to present difficulties due to meteorological and hydrological uncertainties.

This paper presents the methodology and first results of a study that is being carried out for a better understanding as to urbanization affects on hydrological processes and flash flooding in a Mediterranean drainage basin. The specific objectives are evaluating: (1) the basin hydrologic behaviour considering different land uses; (2) the role of local environmental characteristics (local relief, aspect and gradient) and physicochemical soil properties on soil infiltration capacity; (3) spatial and temporal variations in soil hydraulic characteristics; (4) the effect of rainfall patterns and characteristics on erosion and potential flood generation;

Zusammenfassung

Dieser Beitrag zeigt die Methodik und erste Ergebnisse zur Abschätzung des Einflusses von Landnutzungsänderungen und Verstädterung auf verschiedenen räumlichen Skalen am Beispiel des Kleineinzugsgebiets *Ribeira dos Covões* in Zentralportugal. Dabei soll besonders auf den Einfluss der Landnutzungsänderung auf die Abflussverhältnisse eingegangen werden. Dies ist besonders für die Vorhersage von Hochwässern in rasch anwachsenden Stadtbereichen und deren Schadensverminderung durch Anwendung von Hochwasserwarnsystemen wesentlich.

Schlagwörter: Kleineinzugsgebiet, Verstädterung, Oberflächenhydrologie.

Summary

This paper presents the methodology and the first results of a study that is being developed in the *Ribeira dos Covões* micro-catchment, located in central Portugal, to study the impact of different land uses and the urbanization process on spatio-temporal hydrological changes based on a multi-scale approach. The aim of this study is to contribute for a better understanding on how land use changes impact hydrological processes. This is critical for predicting urban floods in fast urbanized areas and their mitigation (e.g. real-time flood warning procedures), which has become crucial for planning, management, and supporting the sustainable development of the basin.

Key words: Experimental basin, urbanization, surface hydrology.

(5) the impact of urban drainage on hydrological processes; and (6) future flood mitigation strategies.

Experimental basin and methods

The study has been performed in *Ribeira dos Covões*, a small experimental basin (620 ha) located in mainland Portugal on the outskirts of Coimbra, the main city in central Portugal (Figure 1). The *Ribeira dos Covões* basin is characterized by a humid Mediterranean climate, with an average annual temperature of +15 ºC and total rainfall of 980 mm in an average year, with strong seasonal and inter-annual variability. Population living in the catchment was estimated at 7000 inhabitants in 2001. Nowadays, the basin is predominantly covered by forest (55.5%) and farmland (13.0%), with a significant presence of artificial surfaces (31.5%). It has experienced significant urbanization in recent years as a result of its proximity to the city of Coimbra and this trend is expected to continue with new urban areas planned and under development. This situation has been considered 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. The spatial variability inside the basin was assessed in order to evaluate the urban impact on hydrological processes. Initially thirteen locations inside the basin were randomly selected and three replicates per location were sampled for physicochemical soil analysis: organic content, particle size, bulk density and water retention capacity. Temporal variability in soil moisture (TDR method), hydrophobicity (Molarity of Ethanol Drop Method) and hydraulic conductivity (through Mini-Disk infiltrometer) were also calculated/measured from the previous four monitoring surveys.

Several hydrological parameters (soil moisture evolution along the experiment, time to runoff start and to runoff stop, runoff volume) were estimated using rainfall simulations at the microplot scale (0.25 m^2) (Figure 2). This methodology was used to provide additional information on different land-uses with different physiographical characteristics. Twenty one rainfall simulation experiments were performed, each lasting for one hour, with a rainfall intensity of 45 mm h^{-1}, based on a portable sprinkler rainfall simulator adapted from Cerdà et al. 1997. The rainfall simulator consists of a quadrangular frame, supported on an extensible simulator support that gives a height of 2 meters above the ground surface, and a set of nozzles (Hardi®) located in the center of the frame. The placement of two spirit levels allows the horizontal installation of the nozzle. There is a manometer between the circuit connection of the nozzle and the system of water supply, which is provided by two manual pumps (Ossatu® each with 6 liters capacity). The structure is surrounded by a plastic curtain to prevent wind interfering with the direction of falling rain droplets. Experiments were performed during dry weather conditions in forest, clear felled areas, agricultural areas (including tilled and abandoned), built-up and construction areas. As the installed plots were kept in place, these experiments will be repeated during wet periods for the same locations.

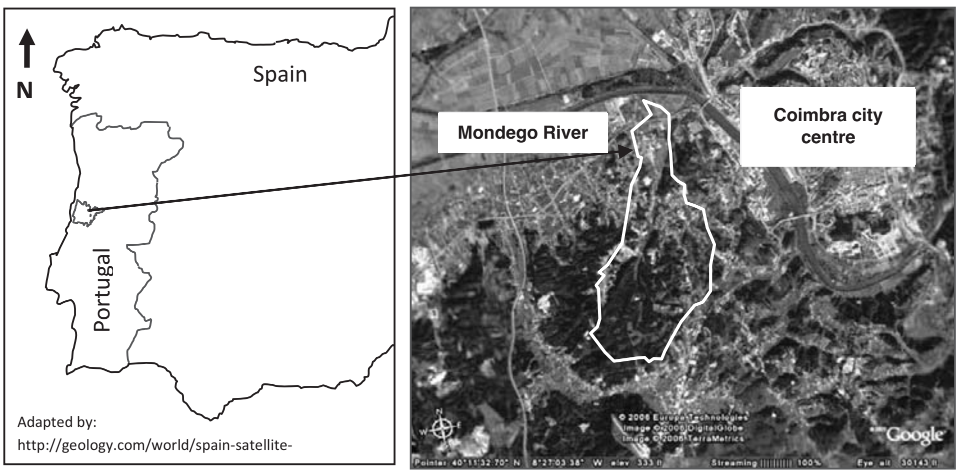

Figure 1: Left: municipality of Coimbra in mainland Portugal.
Right: "Ribeira dos Covões" urban drainage basin location in the city of Coimbra

Abbildung 1: Links: Lagedarstellung der Stadt Coimbra im Zentralbereich Portugals
Rechts: Kleineinzugsgebiet „Ribeira dos Covões" im Stadtgebiet von Coimbra

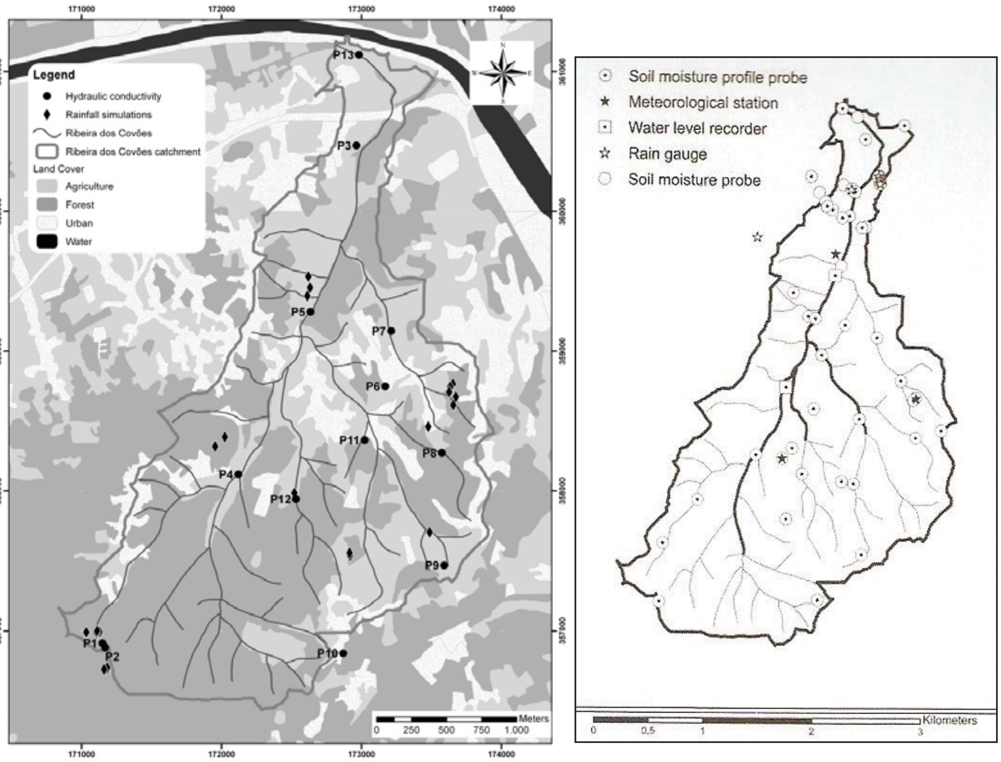

Figure 2: Left: basin land use and experiments location (hydraulic conductivity and rainfall simulation experiments)
Right: monitoring network

Abbildung 2: Links: Landnutzung und Standorte der experimentellen Untersuchungen
Rechts: Beobachtungsnetz

In addition to the *pedon* and plot scale, the study has also focused on hydrological processes at the basin scale. This is being assessed using a continuous recording monitoring network, including a weather station and a water level recorder installed in the basin outlet since 2005. Several rain gauges, temperature and humidity sensors, water level recorders and soil moisture probes have been recently installed for a more complete meteorological network that provides spatial variability inside the study area. The meteorological network will provide 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.

Land use is being analyzed using high resolution remote sensing data. A GIS database of land use changes and development throughout the past 50 years is also under construction based on existing cartographic information and aerial photography. To evaluate the impact of urban areas on hydrological processes, an evaluation of urban intensity and urban drainage systems is under way. Water level recorders in some drainage networks will be installed to measure the runoff collected and carried beyond the basin boundaries.

Results and discussion

Pedon scale

The four hydraulic conductivity monitoring campaigns (Figure 3) were carried out in 2008 after different rainfall events: 78.8 mm rainfall registered eight days before the first campaign in April, 32.8 mm before the second campaign in May, 14.6 mm before June campaign, and 1.4 mm fall before July campaign.

The results revealed a high spatial and temporal variability on soil hydraulic conductivity in the study area, with lower values for land used as forest (average values of 3.3 mmh^{-1}) and higher values for farmland soil (50.0 mmh^{-1}). However, considering the variability over time, the relation between hydraulic conductivity and land use is not clear (e.g. P6 and P10 results, located in aban-

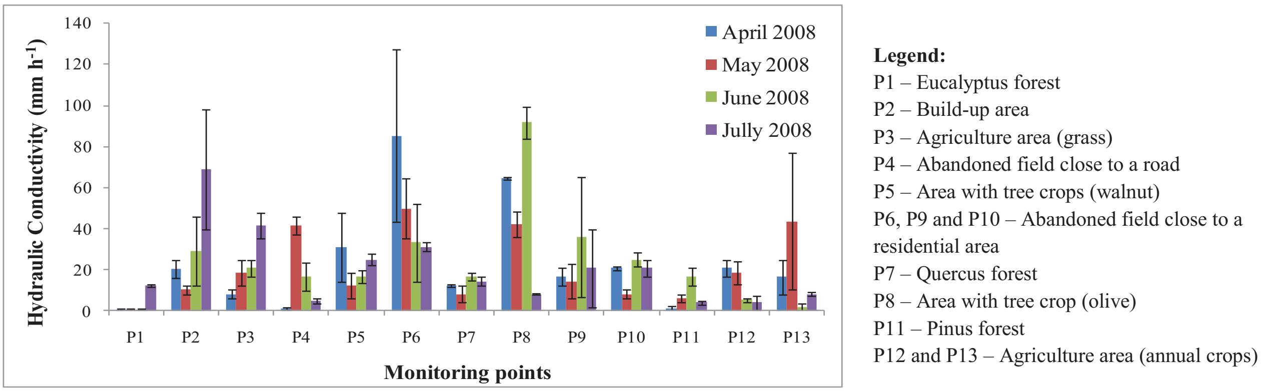

Figure 3: Hydraulic conductivity results for thirteen locations monitored over time (average and standard deviation results)
Abbildung 3: Hydraulische Durchlässigkeit (Mittelwert und Standardabweichung) an dreizehn Standorten und vier Zeitpunkten

doned fields close to residential areas). P1, P7 and P11, despite being forest areas, present different hydraulic conductivity results, but these can be associated with the distinct characteristics of the forests.

The differences in rainfall patterns recorded before each monitoring survey affected soil moisture and water repellency behaviour (Figure 4), which in turn have an important impact on the temporal pattern of hydraulic conductivity. In fact, the lower values recorded in forest areas may have occurred due to the measured higher hydrophobicity. However not all locations showed the same behaviour for the different monitoring surveys, so it is necessary to undertake more measurements in order to understand the important parameters. No statistical correlation was found between hydraulic conductivity, bulk density or field capacity. However organic content ($r = 0.692$, sig. < 0.05), and the soil clay fraction ($r = -0.656$, sig. < 0.05) were important parameters.

Table 1: Soil top layer (0-5cm) properties (bulk density, organic content and clay fraction) of thirteen locations monitored
Tabelle 1: Bodeneigenschaften in 0-5cm (Dichte, organ. Anteil, Tonanteil) an dreizehn Beobachtungstandorten

	Bulk density (g cm^{-3})	Organic content (%)	Clay (%)
P1	1.5	4.2	37
P2	1.3	0.1	16
P3	1.4	2.1	9
P4	1.3	5.6	5
P5	1.4	1.6	15
P6	1.2	6.2	9
P7	1.3	1.9	20
P8	1.2	0.1	4
P9	1.1	4.3	8
P10	1.2	5.6	10
P11	1.5	2.0	48
P12	1.3	2.6	21
P13	1.5	4.0	3

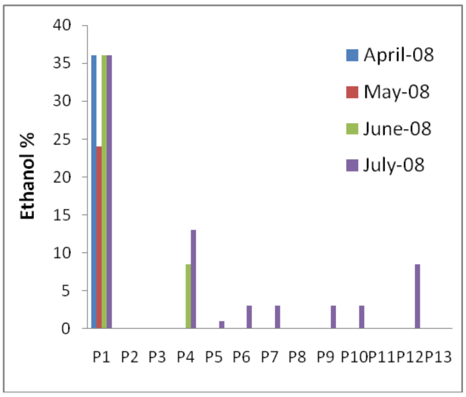

Figure 4: Water repellence results of thirteen locations monitored on soil surface along the time
Abbildung 4: Wasserabweisende Eigenschaften der Bodenoberfläche an dreizehn Standorten

Plot scale

The results for the rainfall simulation experiments are presented in Table 2 and Figure 5.

The results showed different hydrological responses to rainfall for different land uses. According to the results of an Anova statistical analysis, there are significant differences between average runoff coefficients in different land uses. In agricultural areas runoff either did not occur or was negligible. In forest and deforested areas (with a biomass surface cover) the runoff coefficient ranged from 20% to 80% of total rainfall, while in built-up areas the values were higher: 58.5% to 97.9%. However, runoff yield did not seem to

Table 2: Plot characteristics and experimental results
Tabelle 2: Standortseigenschaften und Messergebnisse

Land use	Slope angle (°)	Moisture content (%)		Time to runoff start (min.)	Time to runoff stop (min.)	Rainfall volume (mm)	Runoff volume (mm)
		Before	After				
Forest (n=4)	18±14	5.8±4.9	22.8±12.3	4±2	63±1	45.0	46.6
Deforested (n=3)	8±6	5.1±6.2	26.7±4.7	9±4	68±6		51.2
Tilled agriculture (n=4)	14±11	12.7±7.6	34.8±5.3	-	-		0.0
Abandoned agric. (n=4)	15±3	9.7±0.7	38.6±4.4	-	-		0.0
Build-up (n=6)	36±15	5.5±5.2	29.6±13.4	8±9	64±2		61.7

n: number of rainfall simulations performed

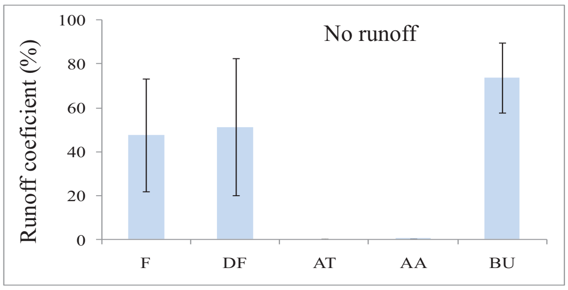

Figure 5: Runoff coefficient results (average and standard deviation) for the different land uses (F: forest, DF: deforested; AT: tilled agriculture, AA: abandoned agriculture, BU: build-up areas)
Abbildung 5: Abflussbeiwerte (Mittelwert und Standardabweichung) bei verschiedenen Landnutzungen (F: Forst, DF: Abholzung; AT: Acker, AA: aufgelassene Flächen, BU: Baugebiet)

be from infiltration excess due to low soil moisture values and quick time to runoff start. Considering that runoff was initiated 1 minute after the beginning of some experiments with low moisture content, Hortonian Flow (Horton, 1933) does not seem to be the main mechanism responsible for flow generation in all land uses. Hydrological processes can be likely explained by soil water repellency and/or macropore collapse.

Concerning the time to runoff stop, in some cases it happened at the end of the rain, but in deforested areas it reached a maximum of 13 minutes after the rainfall ended. This parameter was correlated with surface litter cover (r = 0.460, sig. < 0.05) due to rainfall interception which prevents contact between water drops and soil surface.

Basin scale

The drainage basin shows a non homogeneous runoff pattern over time. In general the runoff coefficients are lower during the dry periods (Figure 6). Despite the higher rainfall amount registered in 2009, the runoff coefficient did not increase, possibly due to urban drainage system development.

Despite the runoff coefficient variability, it is always lower than 10%. Considering the size of the urban area, these results were expected to be higher, but they can be associated with the limestone bedrock and the existence of an urban drainage system. However a more detailed study is neces-

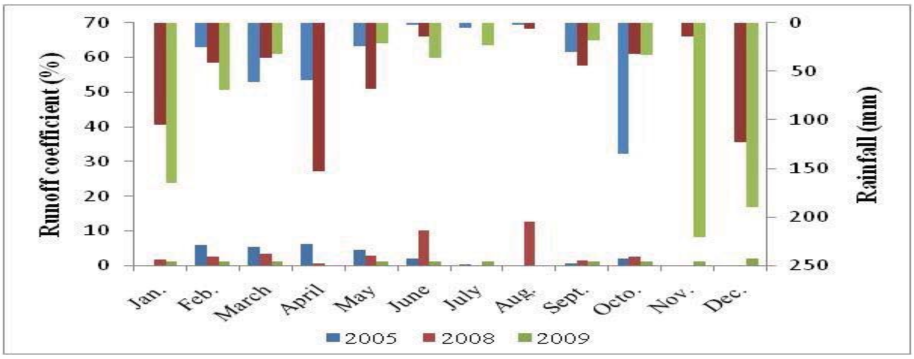

Figure 6: Monthly rainfall and runoff coefficient considering the available data (×: no data)
Abbildung 6: Monatlicher Niederschlag und Abflussbeiwerte bei gegebener Datenlage

sary to understand the impact of previous weather conditions, rainfall patterns and soil moisture content on the runoff response. Similarly, the urban drainage system contribution for this drainage basin.

Conclusions

The initial study results have revealed spatial and temporal variability in hydraulic conductivity and runoff generation in the *Ribeira dos Covões* drainage basin. However results at different scales must be interpreted carefully if we try to upscale the results. For example, although the rainfall simulation experiments replicated the same experimental conditions in different places, allowing a comparison between different land uses. The methodology is limited due to the small plot scale and the specific rainfall characteristics simulated during the experiments (e.g. rainfall intensity). Nevertheless the low hydraulic conductivity and the quick runoff initiation recorded in the rainfall simulation experiments associated with water repellency and basin scale results, indicate that the basin generates quick runoff, which should be considered during floods forecasting.

The initial results presented in this paper need to be validated with more data to assess spatio-temporal variability in the basin, as well as revise the hydrological processes at different scales for different land uses, to understand how they contribute to the basin hydrology. The different hydrological patterns recorded for the land usage demonstrates spatial discontinuities in overland flow processes at the catchment scale. This should be considered for disruptions in landscape connectivity, which has been shown to be a major driving force in overland flow/runoff generation processes and flood risk assessment during urban planning. The aim of the study is to gather information to parameterize, calibrate and validate a spatially-distributed, physical, hydrological model that simulates both the impact of land use change on flash flood response and mitigation planning strategies.

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