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Temporal dynamics of soil moisture and rainfall erosivity in a tropical volcanic archipelago

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ABSTRACT

Soil water availability has a strong role on vegetation conservation and biodiversity, particularly at vulnerable environments such as archipelagos, subject to significant temporal changes of climate and rainfall, which influence soil weathering and erosion processes. Few field studies on hydrology of volcanic islands in the Atlantic Ocean have been developed focusing on soil and water temporal dynamics and conservation, mainly because such studies require data with high temporal resolution, and also due to the financial costs involved with field data acquisition at such remote places. Considering the importance of soil moisture content to several hydrological processes and islands environmental sustainability, this study aimed to investigate the soil water temporal dynamics in relation to different rainfall patterns and also the rainfall erosivity and its temporal variation, and the resulting infiltration depths, during a typical hydrological period, in an experimental plot at the main watershed of Fernando de Noronha, in the Brazilian Atlantic Coast. Rainfall was recorded every 5 min, and soil moisture was intensely monitored by 16 moisture probes, installed at 10–40 cm and 40–70 cm layers, during three years, representing the typical local hydrological regime and seasons. Rainfall bursts pattern were identified and described. Experimental data allowed a hydrological model to be calibrated and validated, providing estimates of infiltration depths, which can be valuable for water resources planning and management. Hydrological patterns were determined for each erosive rainfall, depending on the precipitation peak position, as advanced, intermediate and delayed. The soil water effectiveness was also evaluated and related to the different rainfall patterns. Soil moisture is highest from April to June, close to saturation; whilst for the other months the values were close to the residual value. The rainfall erosivity in the archipelago was identified as moderate to strong, and the most frequent rainfall pattern was the advanced. Fast wetting-drying cycles during the rainfall events were observed, due to rainfall intermittency, evapotranspiration, and to soil hydraulic conductivity. It was observed the prevalence of high moisture indexes, with percentages higher than 40% (extremely effective level) for both investigated depths within the first 70 cm of soil, essential for plant water uptake. The observed rainfall erosivity highlights the importance of defining local strategies for soil and water conservation aimed at water security in the island. Based on a simulation model, which was successfully calibrated (Nash-Sutcliffe Efficiency Index NS = 0.76) and validated (NS = 0.81) for periods in the wet season, high infiltration depths have been identified, which contributes to canopy conservation in the archipelago.

1. Introduction

Rainfall characteristics and bursts patterns are of paramount importance for ecohydrology and biodiversity conservation, affecting infiltration processes and spatio-temporal soil moisture distribution. Intensities of rainfall bursts and their temporal distribution within an event can be more relevant in terms of hydrological processes than does the mean equivalent rainfall rate (Dunkerley, 2011) Table 1.

Rainfall profiles during storm events and their impacts on infiltration, runoff and soil erosion have been largely addressed in literature. De Lima et al. (2012) have verified that the rain storm temporal variability may have a strong influence on runoff discharge and soil losses, the latter being correlated to the rainfall erosivity. Yin et al. (2015) have pointed out that rainfall erosivity is usually better

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Table 1
Classification for interpretation of annual erosivity index of precipitation.

Erosivity – R (MJ mm $ha^{-1}h^{-1}$)	Erosivity class
$R \leq 2452$	Low erosivity
$2452 < R \leq 4905$	Moderate Erosivity
$4905 < R \leq 7357$	Moderate to strong erosivity
$7357 < R \leq 9810$	Strong erosivity
$R > 9810$	Very strong erosivity

Source: Carvalho (2008).

represented by the maximum 30-min intensities of the event. Moreover, rainfall intermittency may affect hydrological processes, such as infiltration depths, conversion of rainfall to soil moisture, and soil losses (Marani et al., 1997, Montenegro et al., 2013; Dunkerley 2015). Indeed, long no-rain periods within an event may reduce soil surface moisture, and enhance infiltration rates.

Rainfall patterns can be classified as proposed by Horner and Jens (1942), as advanced, intermediate, and delayed, according to the part of the event duration in which the peak falls. Several authors (e.g. Cassol et al., 2007; Carvalho et al., 2009; Bazzano et al., 2010; Aquino et al., 2013) adopted the same methodology for the classification of rainfall patterns. Bazzano et al. (2010) have observed higher soil water contents as a result of advanced rainfall patterns, and Xue and Gavin (2008) also verified that early rainfall bursts generate more infiltration than events with late peaks.

According to Flanagan et al. (1988) and Mehl et al. (2011), higher soil loss is expected to take place for intermediate and delayed rainfall patterns. This behavior is a consequence of higher antecedent soil moisture by the time storm peak occurs, reducing infiltration capacity, and thus enhancing runoff.

Soil water content is one of the main abiotic factors controlling vegetation cover and biome sustainability. Moreover, soil water content plays a hydrological control on partitioning rainfall between runoff and infiltration (Brocca et al., 2014). The spatial and temporal variability of soil moisture impacts a variety of ecosystem dynamics in semiarid environments (Vereecken et al., 2008; Porporato and Rodriguez-Iturbe, 2002). In such areas, subject to strong seasonal climate variation, infiltration capacity should vary along the hydrological year, as result of changes in soil moisture (Cerdà, 1997). Castillo et al. (2003) have showed that antecedent soil moisture might play a distinct role for runoff generation in semiarid catchments, depending on rainfall intensity, soil hydraulic conductivity and plant canopy.

Where experimental soil moisture data is available with high temporal resolution, soil water balance models can be very useful to investigate the main components of soil moisture dynamics, in particular the infiltration component. For instance, Brocca et al. (2008) successfully applied the Green Ampt formulation for simulating infiltration and soil moisture temporal variations from unsteady rain, and hence provided insights on the infiltration behavior for three different sites in Europe.

Based on extensive studies at an Swedish Baltic Archipelago, Saona et al. (2010) pointed out that soil water and nutrients gradients controlled vegetation spatial distribution. Soil moisture was scored from very dry to moist, due to its strong seasonal variation, and such scores highlighted the role soil moisture plays on the ecology of the studied islands.

Fernando de Noronha archipelago is located at the Brazilian coast, presents a semiarid climate, has no springs or perennial rivers, and rainfall during short raining season is the main fresh water source. Groundwater is limited and saline. Moreover, surface water is subject to periods of water shortage, during the dry season, highlighting the importance of investigating hydrological processes such as infiltration, directly related to water resources conservation and use in the region.

The archipelago has been largely studied for several aspects, such as geology, geomorphology, biology, soil mapping, heavy metals in soils and climate aspects (Marques et al., 2007; Marques et al., 2014; da Silva et al., 2014, Lopes and Ulbrich, 2015, Lacerda et al., 2015; Fabricio Neta et al., 2016). Lacerda et al. (2015) have highlighted that warming and drying trends are expected to reduce water availability at the Noronha Archipelago in near future. Previously addressing water resources availability, Motta et al. (2008) have investigated surface water quality in reservoirs, and Montenegro et al. (2009) have studied alternatives to increment fresh water accumulation at the main catchments, and also have developed soil hydraulic in situ tests to support future infiltration analysis on the main soil types, particularly for applying the Green Ampt formulation.

Notwithstanding such efforts, infiltration process studies are still lacking in the Archipelago, relating rainfall temporal structure to soil wetting occurrence.

Such condition has motivated the development of a plot scale detailed experimental study for hydrological monitoring at the Archipelagós main catchment, in order to describe main rainfall patterns and investigate fine temporal resolution soil moisture dynamics, essential to ecosystem sustainability. Similar environments around the world may also benefit from the results of such study.

Hence, the purpose of this study is to analyze rainfall erosivity, investigate the influence of different rainfall temporal patterns on soil moisture dynamics, and on soil water effectiveness to plants, evaluating the infiltration component behavior during rainy seasons, based on a three years intensive local scale experiment using high resolution data.

2. Material and methods

2.1. Study area

The archipelago of Fernando de Noronha lies offshore the Brazilian coast, at a distance of 360 km from Natal, Rio Grande do Norte, and 545 km from Recife, Pernambuco, between latitude 3° 50′ and 3° 52′ S and longitude 32° 24′ and 32° 28′ W (Fig. 1). The group consists of 21 volcanic islands, resulting from an eruption 12 million years ago. The main island, which gives the name to the Archipelago, has 17.6 km^2 (Ribeiro et al., 2006).

A central plateau, 50–70 m high, forms the main island, which is limited by steep slopes and scarps, directly submitted to marine abrasion. The climate is tropical semi-arid with well-defined dry and humid seasons (Aw′). Based on 18 years of observations from an automatic meteorological station, the average annual rainfall is 1418 mm, with a rainy season between February and July, and with potential evapotranspiration of 1038 mm per year. There are two well defined seasons, being the wet period usually from March to July and the dry season from August to January (Pessenda et al., 2008). Rainfall patterns (long term cycles and trends), temperatures and potential evapotranspiration time series are presented in Fig. 2, and also the monitored rainfall and soil moisture data.

Due to dry tropical climate with oceanic influence, the rainfall bursts, and the recent volcanic or sedimentary parent material, some soil weathering is observed in the island (Ribeiro et al., 2006), with sediment accumulation at the main surface reservoirs (Montenegro et al., 2009). A view of natural vegetation cover is provided.

2.2. Hydrology, soils and vegetation

Concerning to the Noronha island hydrology, the Maceió River is the main water course of the island, and flows into the Xaréu reservoir. All surface reservoirs at the archipelago are intermittent, drying quickly at the end of the rainy season (Pessenda et al., 2008). For water availability assessment at the main island, Montenegro et al. (2009) described the main catchments of the archipelago, mapping the soil types and land cover, and evaluated their potential to generate runoff, based on the SCS method for hydrological modeling. For the Xareu catchment, in situ soil hydraulic characterizations were carried out.