Journal of Hydrology (2007) **337**, 104–116

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Mechanisms affecting stormflow generation and solute behaviour in a Sahelian headwater catchment

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Received 27 March 2006; received in revised form 22 December 2006; accepted 15 January 2007

KEYWORDS
Hortonian overland flow;
Subsurface flow;
Event water;
Runoff chemistry;
Suspended load;
Isotopic tracing;
Semi-arid zone

Summary The aim of this study was to analyse stormflow processes and the behaviour of solutes therein (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, alkalinity, NO_3^-, SO_4^{2-}, Cl^-, Si), during flood events in tropical semi-arid conditions. The study site was a small Sahelian catchment (1.4 ha) located in northern Burkina Faso. Runoff and rain water was sampled over a 2-year period (1999 and 2000). In addition to dissolved load, suspended load was measured in the stream water collected at the outlet of the catchment. Isotopic tracing using $\delta^{18}O$ was also conducted during two very different flood events. The results indicated that: (i) event water was by far the major contributor to the stream stormflow, with Hortonian overland flow being the main stormflow process at work; (ii) a small fraction of pre-event soil water may have contributed during the recession of heavy flood with wet antecedent conditions; (iii) solute concentrations were higher in runoff compared to rainwater. With the exception of NO_3^- and Cl^-, the highest concentrations were measured at the onset of floods, and almost always decreased during the rising stage of the hydrographs; (iv) a good correlation was found between sus-

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0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2007.01.019

pended load and the concentrations of Ca^{2+}, Mg^{2+}, alkalinity and Si. It was concluded that fast physico-chemical interactions between event water and reactive suspended phases may explain most of the chemical changes between rainwater and floodwater.

Introduction

Since the 1960s, considerable progress has been made in hillslope hydrological research related to the runoff generation process in humid temperate and tropical forests (e.g. Kirkby, 1978; Bonell, 1993). One of the most significant outcomes was the realisation that streamflows react promptly to rainfall inputs due to a rapid mobilisation of ''old water'', i.e. pre-event soil water or groundwater stored within the catchment before the rainfall event (e.g. Kirchner, 2003). This finding was substantiated by stormflow-hydrograph separation based on artificial (^{3}H) (e.g. Crouzet et al., 1970) or natural (^{18}O or ^{2}H) (e.g. Sklash et al., 1976; Neal et al., 1992) isotopes of water, either in isolation or in association with chemical tracers (e.g. Pearce et al., 1986; Grimaldi et al., 2004). Most of the mechanisms invoked for rapid delivery of old water to the stream involve subsurface flows such as the piston effect, exchanges between matrix and macropores, pipe flow, capillary fringe-induced groundwater ridging and rapid effusion from hillsopes (e.g. Mosley, 1979; Gillham, 1984; McDonnell, 1990; Kendall et al., 1999; Uchidaa et al., 2005).

Most of these studies, however, were conducted in humid forested catchments (Burns, 2002), and hence disregarded surface flow processes such as Hortonian overland flow (infiltration excess overland flow) (Horton, 1933; Beven, 2004) which is a well recognized flow process typical of, but not restricted to, semi-arid areas (e.g. Dunne, 1978; Ludwig et al., 1999). Indeed, several studies described areas of humid tropical Africa where Hortonian flow may also occur (e.g. Dubreuil, 1985; Vigiak et al., 2006). Moreover, studies using tracer-based hydrograph separation in environments affected by urban or rural development (e.g. Buttle et al., 1995; Ribolzi et al., 2000a) found that, as opposed to most observations in forested catchments, ''new water'' (i.e. event rain water) can become a major component of stormflow.

In the Sahel, one of the largest inhabited semi-arid regions of the world, vegetation clearing due to increased human pressure (e.g. extension of cultivated land, overgrazing, etc.) and a significant decrease in rainfall rates since the 1970s (Carbonnel and Hubert, 1992) is having negative on-site effects along hillslopes: unprotected soil surfaces are more exposed to raindrop impact and soil erosion (e.g. Karambiri et al., 2003) leading in turn to soil surface crusting, which favours surface flow rather than infiltration. Hence, it is generally accepted that Hortonian flow (infiltration excess overland flow) is the most important process contributing to stormflow, and the infiltration capacity of a variety of soils and soil surface characteristics has been well documented (e.g. Casenave and Valentin, 1992; Vandervaere et al., 1997). In this context, if Hortonian flow is the main contributor to stormflow, this implies that stormflow water is mainly composed of ''new water'' with a similar chemical and isotopic composition as rainwater.

There is still a critical lack of knowledge regarding the chemical composition and behaviour of solutes in stormflow water in the Sahel (Sandström, 1998; Karambiri, 2003). A small number of papers characterised surface and subsurface hydrochemical processes (e.g. Ribolzi et al., 2003) but using simulated rainfall and only at the plot scale. The aim of this present study was to examine storm solute behaviour, on the basis of contrasted events (maximum rainfall intensity, peak discharge, etc.) at the catchment scale. Rainwater and stormflow water were collected throughout a 2-year period (1999 and 2000) in a small Sahelian catchment in northern Burkina Faso. Our main point of interest was to clarify whether Hortonian overland flow is the main stormflow process occuring in this type of environment.

Materials and method

Study site

The study area is located in the Sahelian region of Burkina Faso, close to the village of Katchari, 274 km north of Ouagadougou (Fig. 1). The climate is characterized by a single rainy season from June to September. The average annual rainfall recorded in Dori (13 km east of the studied catchment) from 1925 to 1998 was 512 mm, with a mean monthly maximum of 181 mm in August. Inter-annual rainfall variability is high (244 mm minimum, 784 mm maximum). The mean annual potential evapo-transpiration, calculated using the Penman method, is approximately 2396 mm. The average monthly temperatures from 1928 to 1984 varied between 23° in January and 33° in April. The vegetation is dry savannah bush, characterised by thorny steppes with scattered acacias and a discontinued seasonal herbaceous stratum concentrated on sandy aeolian deposits.

The experimental catchment (1.4 ha) is located in a watershed with a relatively weak longitudinal slope (about 1%) representative of the Sahelian landscape. The soil distribution along the hillslope is similar to that described by Boulet (1978) at Tassamakat (about 50 km north of the study area). Most of the soils are ferruginous soils (i.e. Plinthic Lixisols, Ferric Lixisols and Chromic Lixisols in the World Reference Base terminology; FAO, 1998), Solonetz soils (i.e. Haplic Solonetz) and brown steppe soils with alkali (i.e. Eutric Cambisols) developed from calco-alkaline granitic rocks. The catchment is composed of five soil surface types (Fig. 1) according to classification by Casenave and Valentin (1992): (1) the drying type (DRY) accounts for 59.9% of the catchment area. It mainly consists of to ferruginous soils. Its infiltration capacity at saturation is about 28 mm h^{-1} (Thiombiano et al., 2000). DRY surfaces cover the leeward