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Flood avalanches in a semiarid basin with a dense reservoir network

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SUMMARY

This study investigates flood avalanches in a dense reservoir network in the semiarid north-eastern Brazil. The population living in this area strongly depends on the availability of the water from this network. Water is stored during intense wet-season rainfall events and evaporates from the reservoir surface during the dry season. These seasonal changes are the driving forces behind the water dynamics in the network. The reservoir network and its connectivity properties during flood avalanches are investigated with a model called ResNetM, which simulates each reservoir explicitly. It runs on the basis of daily calculated water balances for each reservoir. A spilling reservoir contributes with water to the reservoir downstream, which can trigger avalanches affecting, in some cases, large fractions of the network. The main focus is on the study of the relation between the total amount of water stored and the largest observable cluster of connected reservoirs that overspill in the same day. It is shown that the thousands of small and middle-sized reservoirs are eminent for the retention of water upstream the large ones. Therefore, they prevent large clusters at a low level of water. Concerning connectivity measures, the actual reservoir network, which evolved without an integrated plan, performed better (i.e., generated smaller avalanches for similar amount of stored water) than numerous stochastically generated artificial reservoir networks on the same river network.

1. Introduction

The north-east of Brazil is a semiarid region characterized by intermittent precipitation events during rainy season and long periods of water scarcity. Reoccurring droughts, sometimes consecutively for several years, produce serious socioeconomic damage. The water – mainly needed for irrigation, human, and animal uses – is vital for the farmers and its availability is at risk during dry periods (Gaiser et al., 2003). To overcome the problem of the low availability of natural water and the high water demand due to dense population, authorities, land owners, and communities have built thousands of on-river water reservoirs of a wide range of sizes, which allow the water stored during the rainy periods to be used during the dry season. Most of the reservoirs have been constructed according to the local needs of the population, especially farmers, without an integrated plan. This has resulted in a complex dense reservoir network, which is extremely difficult to manage (de Araújo et al., 2010; Krol et al., 2011; Lima Neto et al., 2011; Malveira et al., 2012).

Investigations of the hydrological impact of the small reservoirs on large scale water availability have been conducted (Krol et al., 2011; Malveira et al., 2012) using the WASA model (Water Availability in Semi-Arid Environments see, for example, Güntner and Bronstert, 2004; Güntner et al., 2004; Krol et al., 2006) in Brazil and the TEDI simulation model (Tool for Estimating Dam Impacts see, for example, Nathan et al., 2005; Lowe et al., 2005) in Australia. WASA has been developed as a deterministic, spatially distributed model, to quantify water availability in large water-scarce regions. In WASA, the small and middle-sized reservoirs are represented in classes and, therefore, the water balance of these reservoirs is not calculated explicitly. As a first approach, the hydrologic impact of small dams might be quantified as the sum of the single reservoirs. However, the properties of large-scale system cannot be anticipated due to the emergent behavior arising from the interaction between single reservoirs, as Mamede et al. (2012) showed in the case of the overspill avalanches. In that work, self-organized criticality (SOC) was found within the reservoir network. The concept of SOC states that complex behavior can develop in multi-body systems without explicit pressure or constraints from outside the system, evolving either in time or space (Bak, 1996).

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In the present, we go beyond to study the effect of the network topology on the overall dynamics. In particular, we test different network configurations and analyze the water dynamics within these topologies.

To take reasonable decisions within the framework of water resources management at the level of the reservoir network, instead of looking at single reservoirs, an integrated analysis of the entire network is needed. The motivation for this study is to understand the dependence of water availability on the connectivity pattern, since the two components are correlated: The more water is available, the higher is the connectivity among the reservoirs, and thus the more vulnerable is the network to floods. The concept of connectivity in hydrological systems had been widely applied and it is seen as the key driver for many catchment processes (Michaelides and Chappell, 2009). In the present study, connectivity is defined as the efficiency with which water is transported downstream through the network, which is highly influenced by the thousands of reservoirs in the network. As none of the reservoirs features gates to operate in case of flooding, the natural effect of the reservoirs, which reduces the peak discharge of floods downstream, is the only tangible effect of the network on the flood routing. Therefore a better understanding of the role of connectivity is expected to help mitigating flooding problems, improve water quality, and address economic questions. This might be achieved by changing the system when adding or removing specific reservoirs, or changing the attributes.

By applying the method of upscaling, by which the information of small scale units is used to answer questions at a larger scale, a new model has been developed, denoted ResNetM. Following the approach of network theory, the model provides a simple water balance for each reservoir, as well as information about the water distribution in the system over decades (Mamede et al., 2012). A spilling reservoir delivers water to its downstream reservoir, which can lead to further spilling in a cascade way. These spilling connections among reservoirs can lead to catastrophic events extending over large fractions of the reservoir network (Mamede et al., 2012), with severe socioeconomic consequences (Dutta et al., 2003; Zhou et al., 2012). It is, therefore, paramount to understand the dynamics with respect to these spilling avalanches.

The area under focus is the Upper Jaguaribe basin, located in the south of the state of Ceará, Brazil, which is part of the Brazilian semiarid drought polygon (see Fig. 1). The Upper Jaguaribe consists of 24 municipalities with approximately half a million inhabitants. The economy is mainly built on cattle breeding and agriculture, both irrigated and rain-fed. Its catchment area extends over more than 24,000 km^2 and contains between 4000 and 5000 reservoirs distributed over the basin. The outlet of the basin is controlled by its largest reservoir, Orós, which was built in 1961 and has a storage capacity of 1.94 billion m^3. The average annual rainfall in the region is around 780 mm, whereas annual class A pan evaporation rate is three times as high (2500 mm). Despite the numerous reservoirs, a maximum of 150 mm, or 20% of annual precipitation, has been stored in the system. The groundwater resources are poor and often salty because of the crystalline bedrock (Andrade et al., 2008). In the south and in the east of the basin, small regions with sedimentary rocks can be found. The shallow soils, the reduced vegetation cover, and the high temporal variability in rainfall lead to ephemeral or intermittent rivers (Gaiser et al., 2003). The coefficients of variation are up to 1.4 for annual river discharge. Typical runoff coefficients are in the range of 7%, but values as low as 3% have been identified, depending on geological constraints (de Araújo and Piedra, 2009).

Among the thousands of dams there are a few large ones referred to as *strategic*, because they are planned to secure water supply even in the case of several consecutive drought years. Well-designed reservoirs typically yield 40% of the annual direct inflow with an annual reliability of 90% (Campos, 2010; de Araújo et al., 2006). On the other hand, the smallest ones dry out even before the end of the dry season. On average, the reservoirs are between 50% and 70% full at the end of the rainy season and reach a level down to approximately 30–40% of their capacity at the end of the dry season. Although the thousands of small reservoirs are hydrologically less efficient due to their open morphology, they are very important for a democratic distribution of the water (Malveira et al., 2012). They are also energetically efficient, because they raise the water gravity center, demanding less energy to pump water to upstream consumers. In addition, they show a positive impact on the sedimentation of the strategic reservoirs by detaining large amount of sediments further upstream (Lima Neto et al., 2011).

2. Material and methods

After an outline of the model and data that was used, the main indicators to quantify the systems behavior are then introduced. The subsequent section defines additional methods to evaluate the performance of the reservoir network in the context of water

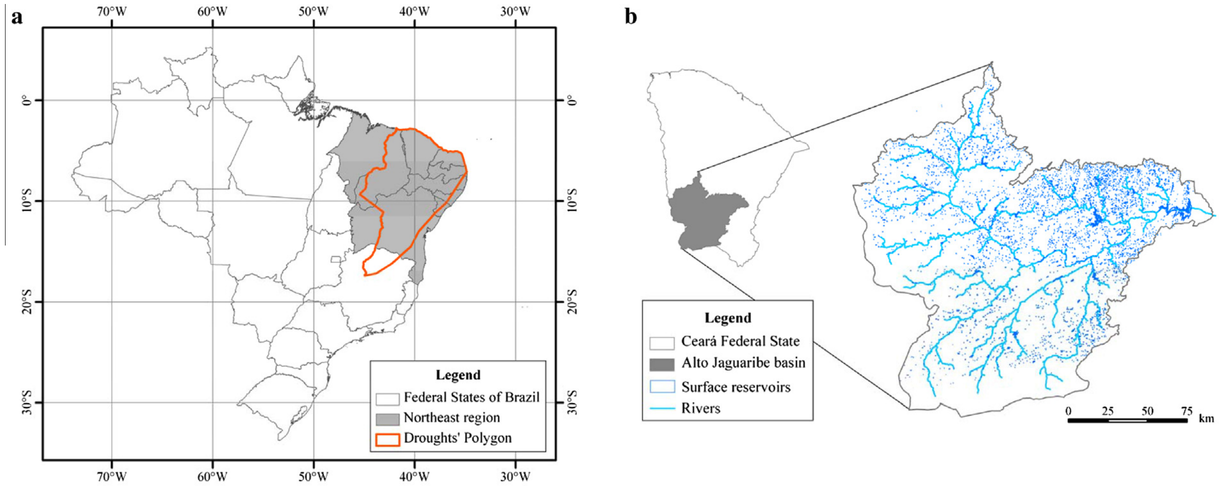

Fig. 1. Overview of the studied area: (a) the Brazilian semiarid drought polygon, and (b) Upper Jaguaribe basin, with main rivers and surface reservoirs (Malveira, 2009).