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A multi criteria analog model for assessing the vulnerability of rural catchments to road spills of hazardous substances

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ABSTRACT

Road spills of hazardous substances are common in developing countries due to increasing industrialization and traffic accidents, and represent a serious threat to soils and water in catchments. There is abundant literature on equations describing the wash-off of pollutants from roads during a storm event and there are a number of watershed models incorporating those equations in storm water quality algorithms that route runoff and pollution yields through a drainage system towards the catchment outlet. However, methods describing catchment vulnerability to contamination by road spills based solely on biophysical parameters are scarce. These methods could be particularly attractive to managers because they can operate with a limited amount of easily collectable data, while still being able to provide important insights on the areas more prone to contamination within the studied watershed. The purpose of this paper was then to contribute with a new vulnerability model. To accomplish the goal, a selection of medium properties appearing in wash-off equations and routing algorithms were assembled and processed in a parametric framework based on multi criteria analysis to define the watershed vulnerability. However, parameters had to be adapted because wash-off equations and water quality models have been developed to operate primarily in the urban environment while the vulnerability model is meant to run in rural watersheds. The selected parameters were hillside slope, ground roughness (depending on land use), soil permeability (depending on soil type), distance to water courses and stream density. The vulnerability model is a spatially distributed algorithm that was prepared to run under the IDRISI Selva software, a GIS platform capable of handling spatial and alphanumeric data and execute the necessary terrain model, hydrographic and thematic analyses. For illustrative purposes, the vulnerability model was applied to the legally protected Environmental Protection Area (APA), located in the Uberaba region, state of Minas Gerais, Brazil. In this region, the risk of accidents causing chemical spills is preoccupying because large quantities of dangerous materials are transported in two important distribution highways while the APA is fundamental for the protection of water resources, the riverine ecosystems and remnants of native vegetation. In some tested scenarios, model results show 60% of vulnerable areas within the studied area. The most sensitive parameter to vulnerability is soil type. To prevent soils from contamination, specific measures were proposed involving minimization of land use conflicts that would presumably raise the soil's organic matter and in the sequel restore the soil's structural functions. Additionally, the present study proposed the preservation and reinforcement of riparian forests as one measure to protect the quality of surface water.

1. Introduction

Releases of hazardous materials caused by accidents during transport in roads are inherently associated to risks that have drawn interest and public concern in recent years worldwide (Inanloo and Tansel, 2016; Inanloo et al., 2016). An effective prevention of these risks can be attained with development of environmentally sustainable road transport networks, an enterprise largely dependent on a proper identification of critical points in the roads as well as on the implementation of efficient security measures for the prevention of accidents in those points. Data from the Brazilian Association for the Chemical Industry (ABIQUIM) regarding the years of 2009 and 2010 show that a major portion (about 60%) of emergency calls and reported incidents related to the transport of hazardous materials in Brazil were connected to road transportation (Almeida, 2010). Besides, the transport of

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dangerous cargo in Brazilian roads grew in the last decades making more probable the occurrence of incidents with severe environmental consequences (CETESB, 2005). In order to minimize the damage caused by accidents involving the transport of hazardous goods, a demand for research focused on the risks of transporting this kind of cargo is currently growing (Cordeiro et al., 2016).

Road accidents are mostly caused by "external events, management factors, mechanical and equipment failure, driver error (Yang et al., 2010)". Immediate consequences of road accidents involving trucks and the transport of hazardous substances include sudden pollution of soils and water, with subsequent damage of terrestrial and aquatic ecosystems and consequent economic loss. The routing of truck tankers transporting hazardous materials has been substantially studied (Akgün et al., 2007; Guo and Verma, 2010; Inanloo et al., 2016; Leonelli et al., 2000; among others), while there is considerable investigation on road network design where evaluation criteria on hazardous materials are defined for appraisal (Das et al., 2012; Frank et al., 2000; Inanloo et al., 2016; Kang et al., 2014; to mention just a few). Most of these studies evaluated travel costs based on link lengths, while in a small number of cases health and societal risks were also taken into account (Inanloo et al., 2016; Verter and Kara, 2001). However, studies specifically addressing the risks to catchments and their components (soils, water, ecosystems) resulting from spills of hazardous substances during road traffic accidents are relatively scarce, especially in the rural environment. In a recent study, Cordeiro et al. (2016) estimated the environmental risk of transporting hazardous substances in roads with the purpose of spotting areas evidencing a high risk of accidents, to be abandoned afterwards as central itineraries, but the study was not explicitly focused on rural catchments. There are also various storm water management models in current use (e.g. Rossman, 2015), but they mostly address the distribution of runoff and pollution yields across urban catchments and not the vulnerability of rural catchments based solely on biophysical parameters.

The main purpose of this study is therefore to develop a framework model for identifying sectors of a road network where the occurrence of accidents may cause significant damage to the environment, namely to soils, water and ecosystems in rural catchments. The approach resorts to the method of Multi Criteria Analysis (MCA), comprising the assembling and processing of biophysical parameters at catchment scale and in a GIS (Geographic Information System) platform, namely soil class, ground slope, land use or occupation, distance to water courses and drainage density. The selected parameters are analogs of key variables appearing in wash-off models and routing algorithms describing the detachment and transport of pollutants in catchments. For that reason, they were considered adequate to represent vulnerability parameters in the MCA. The GIS software was used to process and integrate the spatial data on the vulnerability parameters, a circumstance also observed in other related models (Brown and Affum, 2002).

2. Study area

This study was focused on the Environmental Protection Area (APA – Área de Proteção Ambiental, in Portuguese) of Uberaba River basin, which is located in the Uberaba municipality (State of Minas Gerais, Brazil) and spans the following range of geographic coordinates (Fig. 1): latitude south 19.51°–19.74°; longitude west 47.64°–47.98°. The APA covers an area of approximately 525.27 km^2, distributed within the Uberaba catchment headwaters where anthropogenic pressures are lighter. This region has been protected by the Minas Gerais law nr. 13183/1999, in 1999, because it is considered crucial for the preservation of water resources, freshwater ecosystems and the Cerrado biome, which is a native vegetation that is still present in the area as vestige.

The network of Uberaba River tributaries in the APA is composed of 62 streams and streamlets draining an equal amount of sub-basins (Fig. 1). Water resources in this protected area are abundant and of excellent quality, being used for the public supply of Uberaba, Conceição das Alagoas and Veríssimo towns. The APA is located in the Paraná basin, namely in the North-Northeast portion of this depression. The Paraná basin has been filled with a sedimentary sequence, namely with sandstones and conglomerates dated from the Cretaceous and belonging to the Bauru Group. In the vicinity of water courses, these rocks were overlaid by alluvial and colluvial deposits dated from the Cenozoic (Valle Junior et al., 2010). Topography is characterized by an undulated plateau (Cruz, 2003) whereas soils are mostly represented by red latosols and yellow argisols with average texture (Valle Junior et al., 2013;

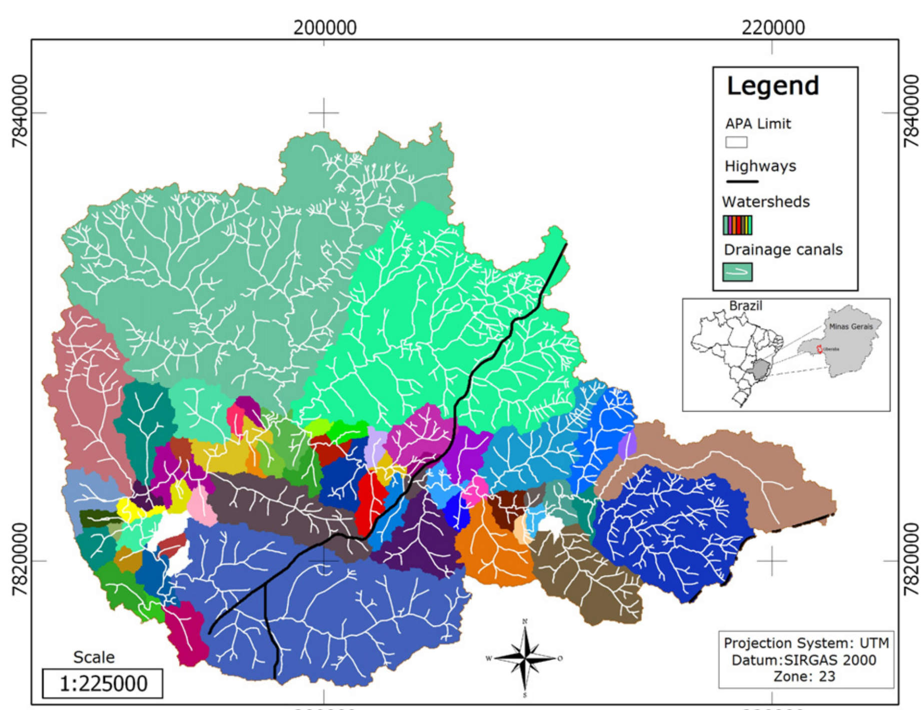

Fig. 1. Location and delineation of APA, the Environmental Protection Area of Uberaba River basin. Drainage network and sub-basins of the APA.