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DINÂMICA HIDROSSEDIMENTOLÓGICA DE PEQUENAS BACIAS HIDROGRÁFICAS FLORESTAIS

TESE DE DOUTORADO

Miriam Fernanda Rodrigues

Santa Maria, RS, Brasil
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DINÂMICA HIDROSSEDIMENTOLÓGICA DE PEQUENAS BACIAS HIDROGRÁFICAS FLORESTAIS

Miriam Fernanda Rodrigues

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Orientador: Prof. PhD. José Miguel Reichert

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elaborada por
Miriam Fernanda Rodrigues

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“Anyone who has never made a mistake has
never tried anything new”.
(Albert Einstein).

“And in the end, it's not the years in your life that
count. It's the life in your years”.
(Abraham Lincoln)

RESUMO

Tese de Doutorado
Programa de Pós-Graduação em Engenharia Florestal
Universidade Federal de Santa Maria

DINÂMICA HIDROSSEDIMENTOLÓGICA DE PEQUENAS BACIAS HIDROGRÁFICAS FLORESTAIS

AUTOR: MIRIAM FERNANDA RODRIGUES
ORIENTADOR: JOSÉ MIGUEL REICHERT
Data e Local da Defesa: Santa Maria, 13 de outubro de 2015.

Áreas cultivadas com florestas de eucalipto têm aumentado no Sul do Brasil e os efeitos sobre os processos hidrossedimentológicos são pouco conhecidos, especialmente em escala de bacia hidrográfica e para áreas em que ocorreu mudança no uso do solo. O modelo Soil and Water Assesment Tool (SWAT) tem sido utilizado em bacias hidrográficas florestais para avaliar e simular o efeito do cultivo de florestas comerciais ou mudança de uso do solo sobre os processos hidrológicos, mas os processos erosivos não têm sido avaliados. O presente estudo objetivou (i) avaliar os efeitos do plantio de eucalipto sobre os processos hidrossedimentológicos e a eficiência e as limitações do SWAT em simular o escoamento superficial e produção de sedimentos (diários e mensais) em bacias hidrográficas embutidas, ocupadas com eucalipto, e em duas bacias hidrográficas pareadas ocupadas principalmente com eucalipto e com campo natural, e (ii) identificar a contribuição das fontes margem da rede de drenagem, as estradas e os povoamentos de eucalipto na geração de duas diferentes frações de sedimentos (< 0,063 mm e 0,063-2 mm) depositados ao longo da rede de drenagem, e de sedimentos em suspensão coletados no exutório de bacias embutidas. O SWAT foi utilizado para avaliar os processos hidrológicos e de erosão em duas bacias florestais embutidas (bacia-0,94 km^2 e sub-bacia-0,39 km^2) e em duas bacias hidrográficas pareadas no Bioma Pampa, uma com campo natural (1,10 km^2) e outra com eucalipto (0,83 km^2). A vazão e a produção de sedimentos medidas nas seções de monitoramento das bacias hidrográficas foram utilizadas para avaliar a sensibilidade dos parâmetros selecionados do modelo e para calibração para as bacias embutidas (2009-2013), e para as bacias pareadas (2009-2013). As séries temporais e os parâmetros estatísticos foram utilizados para avaliar o potencial preditivo do modelo. Para as bacias embutidas, a representação da vazão mensal foi muito boa durante a calibração para a bacia e para a sub-bacia, respectivamente. A representação da produção de sedimentos mensal foi muito boa e satisfatória para a bacia, e insatisfatória para a sub-bacia. As simulações na escala diária foram satisfatórias para a representação da vazão e da produção de sedimentos para a bacia. Para a sub-bacia, a representação da vazão foi satisfatória, mas da produção de sedimentos foi insatisfatória. Para as bacias hidrográficas pareadas, a representação da vazão mensal foi boa durante a calibração para a bacia com pastagem e para a bacia com eucalipto. A representação da produção de sedimentos mensal foi satisfatória para a bacia com pastagem, e muito boa e satisfatória para a bacia com eucalipto. As simulações diárias foram satisfatórias para a vazão em ambas as bacias pareadas. Os resultados sugerem que o modelo SWAT é uma ferramenta promissora para avaliar processos hidrológicos em bacias hidrográficas brasileiras. No entanto, fazem-se necessários mais tempo de monitoramento contínuo das variáveis hidrossedimentológicas e alteração de equações empíricas do SWAT para melhor representar processos erosivos que predominam em cada bacia e para representar os processos hidrológicos e erosivos em escala sub-diária, especialmente para pequenas bacias em que o tempo de concentração é menor do que um dia. As fontes de sedimentos foram avaliadas por meio do uso de propriedades geoquímicas, determinadas por análises de espectrometria de massas com plasma e de fluorescência de raios-X. A contribuição das fontes de sedimentos foi determinada em pontos espacialmente distribuídos ao longo do canal principal da bacia. Amostras de sedimento de um ponto de coleta foram utilizadas para avaliar a contribuição das fontes da área de contribuição à montante desse local de interesse e para indicar o a diferença da contribuição dessas fontes em diferentes localizações à jusante. Para avaliar se as diferentes frações de sedimentos tem origem semelhante, duas frações de tamanho de partículas das fontes e amostras de sedimento fino (< 0,063 mm) e grosso (0,063-2 mm) foram analisadas. A técnica fingerprinting indicou que o tamanho das partículas e localização das fontes dentro da bacia hidrográfica são os principais fatores que afetam a contribuição das fontes para a produção de sedimentos finos e grossos. As fontes mais próximas do local de amostragem são as potenciais fontes de sedimentos, sendo provável que essa fonte de sedimentos será dominante na amostra de sedimentos, principalmente para as frações grossas. Com base na análise de classificação, a contribuição relativa de cada fonte indicou que a principal fonte de sedimentos foi a margem do canal da rede de drenagem. Os resultados da modelagem e identificação das fontes de sedimentos contribuem para uma melhor compreensão do efeito do uso do solo ou da alteração no uso sobre a produção de sedimentos na escala de bacia hidrográfica, que são úteis e podem ser utilizados como ferramenta de gestão dos recursos naturais.

Palavras-chave: Hidrologia florestal. Erosão e sedimentologia. Modelo SWAT. Bacias hidrográficas embutidas. Bacias hidrográficas pareadas. Fingerprinting approaching. Florestas comerciais.

ABSTRACT

Doctoral Thesis
Graduate Program in Forest Engineering
Federal University of Santa Maria

HIDROSSEDIMENTOLOGY DYNAMICS OF SMALL FOREST WATERSHEDS

AUTHOR: MIRIAM FERNANDA RODRIGUES
ADVISOR: JOSÉ MIGUEL REICHERT
Place and Date of the Defense: Santa Maria, October 13, 2015.

Areas cultivated with eucalyptus forests have increased in Southern Brazil, and the effects on hydrosedimentological processes are not well known particularly at the watershed scale and in watersheds where land use has been changing. The Soil and Water Assessment Tool (SWAT) model has been applied in a few forested watersheds to evaluate and predict effects of commercial forest cultivation or land use change in hydrological processes, whilst erosion processes has not been the main goal. The present study aimed (i) to evaluate the effects of eucalyptus plantation on hydrosedimentological processes, and to evaluate the efficiency and limitations of the Soil and Water Assessment Tool (SWAT) model to simulate streamflow and sediment yield (daily and monthly) in nested eucalyptus watersheds and in two paired watersheds with eucalyptus and grassland, and (ii) to identify the contribution of the bank channel, unpaved roads and eucalyptus stands sediment-sources for two different size fractions of sediment (< 0.063 mm and 0.063-2 mm) deposited along the drainage network, and suspended sediment collected in the outlet of small watersheds. SWAT was used to evaluate hydrological and erosion processes for two nested forest watersheds (watershed-0.98 km^2 and sub-watershed-0.39 km^2) and two paired watersheds in Pampa Biome, one with grassland (1.10 km^2) and other with eucalyptus (0.83 km^2). Measured streamflow and sediment yield at the watersheds outlets was used to evaluate model sensitivity to selected model parameters, and for calibration from 2009 to 2013 for nested watersheds, and from 2009 to 2013 for paired watersheds. Time series plots and standard statistical measures were used to verify model predictions. For nested watersheds, predicted monthly streamflow was "very good" during calibration for the watershed and for the sub-watershed, respectively. Predicted monthly sediment yield was "very good" and "satisfactory" for the watershed, and "unsatisfactory" for the sub-watershed. Simulations for daily time-scale were "satisfactory" to predict streamflow and sediment yield for the watershed. For the sub-watershed, predicted streamflow was "satisfactory", but sediment yield was "unsatisfactory". For paired watersheds, predicted monthly streamflow was "good" during calibration for the grassland watershed and for the eucalyptus watershed. Predicted monthly sediment yield was "satisfactory" for the grassland watershed, and "very good" and "satisfactory" for eucalyptus watershed. Daily simulations were "satisfactory" to predict streamflow in both grassland and eucalyptus watersheds. The results suggest that the SWAT model is a promising tool to evaluate hydrological processes in Brazilian watersheds. However, more field work with continuous monitoring is required and empirical equations of SWAT must change to better represent the processes that predominate in each watershed and to represent the hydrological and erosion processes in sub-daily time-scale and, especially, for small watersheds [illegible] time of concentration is less than one day. Sediment-sources was evaluated using geo[illegible] properties, determined by inductively coupled plasma mass spectrometry and X-ray fluorescence analyses, and the data used to calculate proportional contributions of sediment. Source contributions were determined at points spatially-distributed along the main channel of the watershed. Source determination for in-stream sites was done using samples collected in one spot to evaluate source-contribution of area upstream of this site of interest to indicate how different sources dominate at different downstream locations. To examine whether different size-fractions shared similar origins, two size fractions of both source and suspended samples including fine (<0.063 mm) and coarse (0.063–2 mm) particles were analyzed. Fingerprinting approach indicated particle-size and location of sources within a watershed are major factors affecting the measured contribution of sources for coarse and fine sediments. The closer a sediment sampling site is to a potential source, the more likely this sediment-source will dominate the sampled material, especially for coarse particles. Based on the classification analysis, the relative contribution of each source to eroded sediments was bank channel, i.e. from the stream network. Modeling results and sediment-source identification can provide an improved understanding effect of land use or change in land use on sediment yield in watershed scale, which are useful and may be used as a management tool of natural resources.

Keywords: Forest hydrology. Erosion and sedimentation. SWAT model. Nested watersheds. Paired watersheds. Fingerprinting approaching. Commercial forests.

CONTENTS

1 INTRODUCTION

Increase in forested areas with fast-growing species in Southern Brazil is due to growing demand for forest products, especially those from eucalyptus species. Areas traditionally used for agriculture and livestock have been and are being incorporated into forest production system, particularly those with some limitation to grain production, such as lands with high slope and low chemical and physical soil fertility. Despite the contribution to State economy, planted area increase of exotic forests in different regions has generated environmental concerns of possible soil and water degradation.

Implementation effects of Eucalyptus ssp. stands are still unknown and there are uncertainties about the ability of different ecosystems and biomes in supporting planted forests without compromising soil and water resources. Among the concerns are the possibilities of increased evapotranspiration and reduced availability and water storage in the soil, reducing the average flow and increasing erosion processes.

Eucalyptus plantations may control surface runoff, reduce peak flow, and decrease soil loss and nutrients through runoff. These control effects become more efficient as eucalyptus grows and develops. However, intense changes in land use may promote changes in the dynamics of erosion and sediment yield, with consequent change in the sediment yield contribution of each potential sediment-source.

Hydrosedimentological techniques of continuous monitoring and processes modeling in watersheds are efficient tools to evaluate effects on water resources caused by changes in land use and management. Studies with nested and/or paired watersheds represent valuable tools for analyzing the impacts of land use and soil management on the hydrological regime. Such studies allow watershed analysis of basins that have downstream-propagated processes, for nested watersheds, and to compare two (or more) closely-located watershed with similar characteristics with respect to size, geology, slope, and vegetation, where one has land use change while the other has its natural condition preserved. Bosch and Hewlett (1982) made a review of 94 catchment experiments and observed that the direction of change in water yield following forest operations – from planting to harvest - can be predicted with fair accuracy since no experiments, with the exception of perhaps one, have resulted in reductions in water yield with reductions in forest cover, or increases in yield with increases in cover. However, few studies have been conducted to assess the hydrological behavior in nested and paired watersheds occupied with eucalyptus plantation, whilst erosion studies also are incipient.

Unlike issues related to water availability, the impacts of eucalyptus forests in erosion and sediment yields are widely unknown, despite significant environmental degradation such as erosion on roads and on sub-surface and drainage network, with stream network bank-collapse and silting. Thus, obtaining information on hydrological and erosion dynamics in areas occupied by forest stands, either under a history of forest cultivation or under recent incorporation into forestry, is highly relevant.

Mathematical models are important tools for understanding hydrosedimentological processes, simulation of scenarios, and decision making for planning the rational use of natural resources. A comparison of mathematical bases of eleven leading watershed-scale hydrologic and nonpoint-source pollution models was made by Borah and Bera (2003), namely: Agricultural NonPoint−Source pollution model (AGNPS), Annualized Agricultural NonPoint Source model (AnnAGNPS), Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS), ANSWERS−Continuous, CASCade of planes in 2−Dimensions (CASC2D), Dynamic Watershed Simulation Model (DWSM), Hydrological Simulation Program – Fortran (HSPF), KINematic runoff and EROSion model (KINEROS), the European Hydrological System model (MIKE SHE), Precipitation−Runoff Modeling System (PRMS), and Soil and Water Assessment Tool (SWAT. The authors concluded that SWAT is a promising model for long-term continuous simulations in predominantly agricultural watersheds, as highlighted by Bonumá et al. (2015). The comparison of applications of SWAT, HSPF and DWSM models (Borah and Bera, 2004) indicated that the most promising long-term continuous simulation model was the SWAT model.

The SWAT (Arnold et al., 1998) model was developed by the United States Department of Agriculture’s Agricultural Research Service (USDA-ARS) and the Texas A&M University. The model Soil and Water Assessment Tool (SWAT) has been widely used successfully to assess the effects of land use and soil management on hydrology, sediment yield, and water quality. Most of the applications have been driven in the U.S. and Europe (Gassman et al., 2007). In Brazil some studies (Bonumá et al., 2015; Bressiani et al., 2015) were done for the hydrological and sedimentological simulation and delivery of nutrients to springs in rural watersheds, including the assessment of the impact of different agricultural scenarios in the sediment yield and water quality. As SWAT was developed for use in temperate regions, when used in tropical and subtropical climates the model requires parameterization and calibration for later simulation of future scenarios of land use and management recommendations.

Furthermore, hydrosedimentometric monitoring and processes modeling should be associated with identification techniques of sediment-producing sources to elucidate effects of management practices on sediment yield and to evaluate the dynamic interrelationship between sources, in order to propose soil and water conservation measures to reduce environmental impacts and increase productivity.

Contribution of sediment-producing sources to total sediment yield has been investigated predominantly in agricultural watersheds with evidence of erosion and sediment deposition, and deforestation to prepare land for agriculture production, or in forest areas harvested and site prepared for new planting. However, information about sediment-producing sources is incipient in areas of forestry production along the cultivation cycle. In river basins or watersheds comprised mainly with cultivated forest stands, the main source of sediment yield may not be forest, due to the ability of forest canopy to protect the land from erosion. As watershed-scale processes are dynamic and complex, the effects of erosion can be minimized with the cultivation of planted forests and/or transferred to other land uses in watershed sites, and may be observed more frequently in drainage and roads network. Thus, reducing the sediment yield or changing the contribution of each sediment-source.

Nevertheless, there are no studies that evaluated fine (suspended) and coarse-size fractions. Sources of different sediment-size fractions may vary because of different entrainment processes and transport characteristics. Consequently, depending on the particular process is a given watershed, the size-fraction used in tracing study to identify the primary sources needs to be carefully selected. Most of the sediment which enters the system is not transported all the way to the watershed outlet, and thus sediment yield at the outlet of a watershed represents a small portion of the total sediment produced in the watershed as a result of all operative erosion processes.

1.1 Objectives

The objectives of this study were to:

(i) Evaluate the efficiency and limitations of the Soil and Water Assessment Tool (SWAT) model to simulate different time-scales (daily and monthly) for streamflow and sediment yield, in nested eucalyptus watersheds and paired eucalyptus and grassland watersheds, and quantify the effects of eucalyptus cultivation on hydrosedimentological processes in nested watershed; and

(ii) Apply a sediment source fingerprinting approach to discriminate sources for two different size fractions of sediment (< 0.063 mm and 0.063-2 mm) deposited along the drainage network, and suspended sediment collected in the watershed outlet of a small watershed with eucalyptus stands; evaluate if the coarse sediment deposited in the bed channel has the same origin as the suspended sediment in nested watersheds; and evaluate the fingerprinting approach as a contributor to the SWAT model sediment modeling.

1.2 Hypothesis

In order to achieve these objectives, the study was conducted based on the hypotheses described below:

(i) SWAT is able to represent the hydrology and sediment yield for small, paired and nested watersheds covered with eucalyptus stands and with grassland, in different time-scales. The SWAT output predicts that eucalyptus cultivation provides low streamflow and sediment yield, and grassland generates high streamflow and sediment yield.

(ii) Fingerprinting approach properly characterizes sediment-sources of fine (< 0.063 mm) and coarse (between 0.063 and 2.00 mm) sediments. In forested watershed with commercial eucalyptus stands the main sediment-source is not influenced by eucalyptus, and this information agrees with SWAT outputs.

1.3 Outline

This thesis is organized in six chapters. Chapter 1 is an introduction with the motivation and overview of the thesis, objectives and hypothesis of this research. Chapters 2, 3 and 4 describe the methodology, the results and the references, which are presented in three scientific articles as follows: Article I - Ecohydrological modeling of nested eucalyptus watersheds; Article II - Paired watersheds with eucalyptus and grassland in Brazilian Pampa Biome: Ecohydrological modeling with swat; Article III - Sediment fingerprinting in nested watersheds cropped to eucalyptus and riparian forest. Chapter 5 consists of a general discussion. Chapter 6 presents conclusions for the all thesis based on the hypotheses, and this chapter is followed by References.

2 ARTICLE I: ECOHYDROLOGICAL MODELING OF NESTED EUCALYPTUS WATERSHEDS

Abstract

Areas cultivated with eucalyptus forests have increased in Southern Brazil, and the effects on hydrosedimentological processes are not well known, particularly at the watershed scale. The Soil and Water Assessment Tool (SWAT) model has been applied in a few forest watersheds to evaluate and to predict hydrological processes, but erosion processes has not been the main goal. In this study, SWAT was used to evaluate hydrological and erosion processes for two nested forest watersheds (Watershed-0.98 km^2 and Sub-watershed-0.39 km^2) in Southern Brazil, both cultivated to eucalyptus and residual riparian native forest. Measured discharge at the watersheds' outlets was used to evaluate model streamflow sensitivity to selected parameters and for calibration from 2009 to 2013. Time series plots and standard statistical measures were used to verify model predictions. Predicted monthly streamflow was "very good" during calibration for Watershed (NSE = 0.97, RSR = 0.17, PBIAS = 1.3% and R^2 = 0.97) and for Sub-watershed (NSE = 0.83, RSR = 0.41, PBIAS = 8.6% and R^2 = 0.84). Predicted monthly sediment yield was "very good" (NSE = 0.90 and RSR = 0.32) and "satisfactory" (PBIAS = 36.2%) for Watershed, and "unsatisfactory" for Sub-watershed. Simulations for daily time-scale were "satisfactory" to predict streamflow (NSE = 0.80, PBIAS = -1.90, and RSR = 0.45) and sediment yield (NSE = 0.55 and R^2 = 0.55) for Watershed. For Sub-watershed, predicted streamflow was "satisfactory" (NSE = 0.47 and R^2 = 0.73), but sediment yield was "unsatisfactory". The results suggest that the SWAT model is a promising tool to evaluate hydrology in Brazilian watersheds. However, especially in forest nested watersheds with limited data availability, the evaluation of model goodness-of-fit needs to consider hydrological and sedimentological processes for different time steps and size watersheds, and it also needs to take into account the relationship among effects of these processes when up-scaling from the smaller to the larger watersheds.

Keywords: forest hydrology; erosion and sedimentation; SWAT model; commercial forests.

2.1 Introduction

Studies on the establishment of environmental quality standards, as well as impact assessments on watersheds as planning units are required by private and government agencies

(Rodrigues *et al*., 2014). Few studies, however, have provided information on the effects of forests on erosion and sediment yield at the watershed scale in tropical and subtropical regions (Vital *et al*., 1999; Ranzini & Lima, 2002), and there are uncertainties concerning the effectiveness of commercial forests in erosion control, either due to type of forest cultivated or canopy coverage (Porto *et al*., 2009). Although forest canopy provides soil surface protection, even for eucalyptus which provides less-dense canopy (Porto *et al*., 2009), management operations, harvesting, construction, and maintenance of roads in eucalyptus plantations increase susceptibility to water erosion (Schoenholtz *et al*. 2000; Sheridan *et al*. 2006; Ferreira *et al*. 2008; Porto *et al*. 2009; Oliveira, 2011).

Little information is available on hydrological behaviors of forest watersheds at different spatial scales. Detailed descriptions and characterizations of hydrosedimentological processes at different scales are fundamental for using mathematical models, given that modeling has shown great potential to serve as a tool for describing complex natural processes such as those that occur in watersheds. However, the dynamics in which complex processes and sediment transfer occur at different scales are still largely unknown (Duvert *et al*., 2012). Configuration of hydrologic response changes with spatial scale, where heterogeneities being greater at larger scales of increased watershed size (Singh & Woolhiser, 2002). Therefore, few studies evaluate scale effects on erosion and sediment yield, especially in forest watersheds.

Modeling studies in areas occupied by forests are important since the vast majority of models used to predict erosion and sediment yield were developed for agricultural and not forest areas (Rodrigues *et al*., 2014; Oliveira, 2014). Further, results of these studies can be used to assist in planning improvements in soil and water conservation practices (Arnold *et al*., 1999; Jha *et al*., 2006; Borah *et al*., 2006). To perform these functions models must be able to simulate hydrologic processes (Oliveira, 2014; Meaurio *et al*., 2015) and track the transference of sediments and pollutants to the drainage network.

The SWAT model (Arnold *et al*., 1998; Arnold & Fohrer, 2005) has been widely used with good results to evaluate the effects of land use and soil management on hydrology, sediment yield, and water quality (Borah *et al*., 2006). In Southern Brazil, SWAT has good potential to be used as a support tool for planning appropriate land uses, on monthly and annual scale, for improving water quality in rural areas with annual crops (Uzeika *et al*., 2012; Bonumá *et al*., 2012, 2013), but it was not used in rural areas containing eucalyptus forest as the major land use. Therefore, SWAT must be critically examined for its appropriate use in tropical small watersheds because the model was originally designed for temperate regions

(Strauch & Volk, 2013) and for large watersheds (Arnold *et al*., 1998) where the time of concentration is greater than one day. When applied in regions with scarce or incomplete data and where climate, soils, plants and agricultural management practices differ from temperate environments, parameters calibration is necessary (Bieger *et al*., 2015). One major concern is the simulation of perennial tropical vegetation due to absence of dormancy and/or long cycle for maturity, as in eucalyptus species.

We aimed to evaluate the effects of eucalyptus cultivation on hydrosedimentological processes in sub-watersheds and to evaluate the efficiency and limitations of the Soil and Water Assessment Tool (SWAT) model to simulate at different time-scales (daily and monthly) the runoff and sediment yield in nested eucalyptus watersheds.

2.2 Materials and methods

2.2.1 Study area

The Terra Dura Forestry Watershed is comprised of two watersheds: the main and the nested, both under forest cover and located in the Jacuí River Watershed. This watershed is found in the physiographic region Central Depression of Rio Grande do Sul State, in Southern Brazil (Figure 1). The larger watershed, with an area of 0.98 km^2, is called "Watershed", and the nested watershed is called "Sub-watershed", with an area of 0.39 km^2.

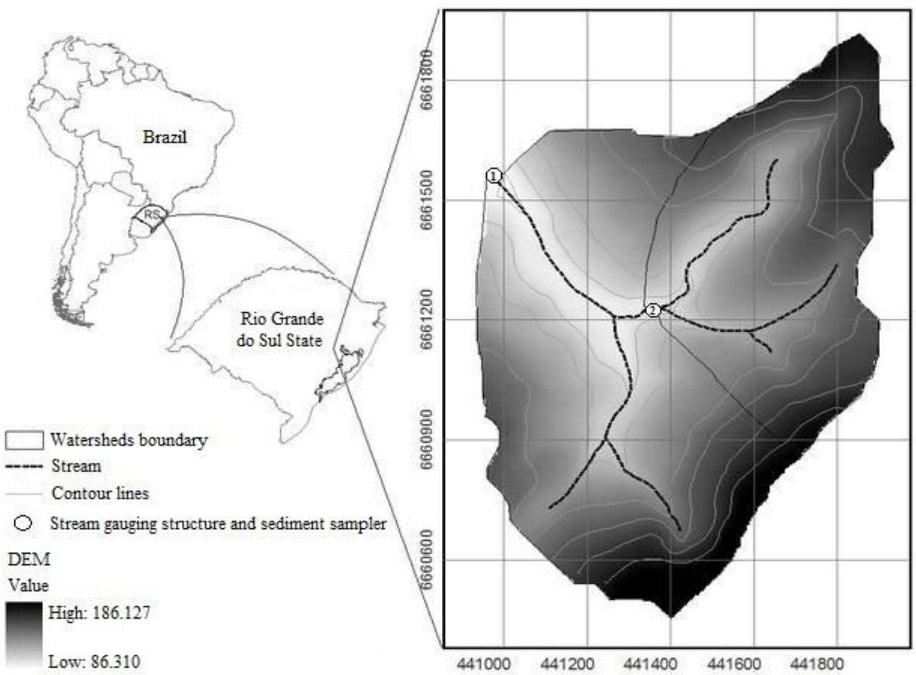

Figure 1. Location and contourlines of the forest Watershed (1) and Sub-watershed (2), in Eldorado do Sul-RS, southern Brazil.

Climate is classified by Köppen climatic classification as Cfa - humid subtropical with hot summers (Alvares *et al*., 2013). Average annual rainfall is 1440 mm, with a monthly average of 120 mm. Most rainfall occurs from June to August in terms of rainfall volume and duration and number of rainy days (Bergamaschi *et al*., 2003; Bergamaschi *et al*., 2013). Average long-term erosivity for the region is 5813 MJ ha^{-1} mm^{-1}, calculated with the equation proposed by Lombardi Neto and Moldenhauer (Silva, 2004). Geology of the area consists of intrusive igneous rocks, syenogranites corresponding to Intrusive Suite Dom Feliciano - Lithofacies Serra do Herval, Neoproterozoic period (2500 Ma) (Ramgrab *et al*., 2004).

Soils on site are classified as *Argissolo Vermelho*, *Argissolo Amarelo*, *Argissolo Vermelho-Amarelo*, *Cambissolo* and *Planossolo* (Costa *et al*., 2009, Brazilian Soil Classification System - Embrapa, 2006) or Ultisols (3), Inceptisols (1) and Planosols (1) (Soil Taxonomy - USDA, 1999) (Figure 2). Soil textural gradient is greater in Ultisols and Planosols (Oliveira, 2011), where sandy texture in surface horizons (A + E) provides fast water infiltration which decreases in textural B horizon due to low permeability. Subsurface discharge causes removal of smaller particles from soil, forming channels called pipes.

Predominant land use consists of commercial forest production, with stands of young and old eucalyptus trees (planted in 1990, 2001, 2004, 2005, and 2010); permanent preservation areas (PPA), i.e., riparian native vegetation; and unpaved roads (Figure 2). Soil cover in young stands is provided by grass and legume species growing between tree rows, whilst for old stands it is provided by undergrowth or by a litter layer which increase soil surface protection against the effects of soil erosion agents.

Watershed and Sub-watershed are characterized by a drainage network of third and second order (Strahler, 1957), respectively, both with deposits of coarse sediments (sand and gravel) where channels margins are composed of sandy material and are highly susceptible to water erosion.

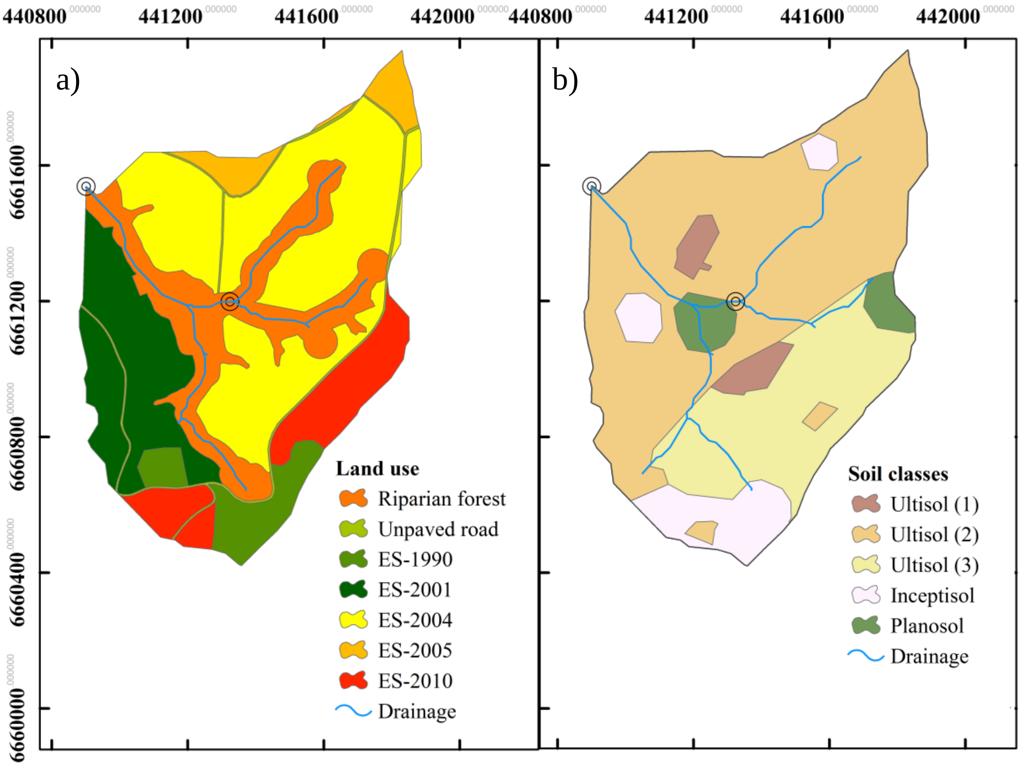

Figure 2. Land use and (a) soil classes (b) of the studied watersheds, in Eldorado do Sul-RS, Southern Brazil. *ES: eucalyptus stand (ES) planted in 1990, 2001, 2004, 2005, and 2010; **Ultisol (1): *Argissolo Vermelho*; Ultisol (2): *Argissolo Amarelo*; Ultisol (3): *Argissolo Vermelho-Amarelo*; Inceptisol: *Cambissolo Háplico*; Planosol: *Planossolo Háplico*.

2.2.2 Hydrosedimentometric monitoring

Hydrosedimentometric monitoring was conducted from 02/16/2011 to 06/31/2013 in automated monitoring sections, instrumented with sensors for water level (limnigraphs), turbidity (turbiditymeters), and rainfall (rain gauges). Sensors were installed near the triangular weirs installed at watershed outlet, whereas dataloggers were programmed to record data at fixed 10-minute intervals.

Suspended sediment was sampled manually during rainfall-runoff-sediment events with a USDH-48 sampler (Edwards & Glysson, 1998) to obtain time series data of suspended sediment concentration determined by the evaporation method (Guy, 1969). Due to the need continuous data acquisition, turbidity measurements were used for estimating suspended sediment concentration. This device provides data for estimating the concentration of suspended sediments based on the relationship between suspended sediment concentration, obtained either during flood events or from sediment concentrations prepared in the laboratory, with fine sediments collected from the drainage network.

Bed load was monitored with a BLH-84 sampler. Direct measurements of bed discharge of sediments were conducted across the whole section width at five equidistant points, collecting 40 subsamples to compose a sample. After collection, samples were taken to the laboratory where sediment load was quantified by drying and weighing. Besides the direct method using samplers, a bathymetric survey was also conducted at the beginning and at the end of the monitoring period to quantify sediment volume retained by the weir. The triangular weir has the capability of accumulate flood waves and reduce flood ability to transport coarser particles, which are deposited upstream of the weir.

Total suspended sediment yield was determined from the integrated solid discharge obtained during automatic monitoring period, whilst the total bed discharge of sediments was determined dividing the total sediment accumulated in the weir in one year by the number of the days in the year. Total sediment yield was determined by the sum of the suspended and bed sediment yield.

For the Watershed the rainfall was 1164.42 mm, the sediment yield was 40.23 Mg km^{-2}, and the average streamflow was 0.00464 m^3 s^{-1} during the period from 02/15/2011 to 12/31/2011; and from 01/01/2012 to 12/31/2012 the rainfall was 1338.96 mm, the sediment yield was 64.44 Mg km^{-2}, and the average streamflow was 0.00481 m^3 s^{-1}. For the Sub-watershed the sediment yield was 38.44 Mg km^{-2}, and the average streamflow was 0.00161 m^3 s^{-1} during the period from 02/15/2011 to 12/31/2011; and from 01/01/2012 to 12/31/2012 the sediment yield was 93.87 Mg km^{-2}, and the average streamflow was 0.00073 m^3 s^{-1}.

2.2.3 SWAT model

The SWAT model is an ecohydrological model for the watershed scale, usually applied in continuous-time simulations, which can be discretized on monthly, daily and sub-daily time-scales (Arnold *et al*., 1998). Thus, input data to feed the model must be adjusted to spatial and temporal dynamics of processes occurring in the target watershed. Required input data are cartographic databases as data layers and tabular data, which are inserted through an appropriate interface. Required layers are digital elevation model (DEM), soil classes, land use/management, and watershed limits.

An interface developed between SWAT and ArcSWAT, in addition to facilitate data input in the model, automatically subdivides the watershed into sub-sections based on DEM and drainage network and then lists the input data for each sub-watershed. Each cell in a DEM is assumed to flow to one of eight neighboring cells according to steepest-slope direction. SWAT simulates a watershed by dividing it into multiple sub-watersheds, which are further divided into hydrologic response units (HRUs) as the product of overlaying soils, land use, and slope classes.

Topographic data were obtained by digitizing topographic contour lines with 5-m intervals. The digitized contour vectors were used to create Triangular Irregular Network (TIN) for generating Digital Elevation Model (DEM) with 5-m spatial pixel resolution. The DEM, watershed outlet point, and digitized drainage network were used to delineate and to partition the watershed into sub-watersheds and reaches. The slope map was divided in three slope classes: 0-2%, 2-10%, and >10%, as recommended for non-hilly topography. Information extracted and calculated from the DEM includes overland slope, slope length, and elevation corrections for precipitation and evapotranspiration.

Land use data over the study period were determined by field surveys, assisted by a geographic positioning system with GIS software and checked in Google Earth®. Main land uses in the watershed consist of cultivated eucalyptus (planted in 1990, 2001, 2004, 2005, and 2010), native riparian forest, and roads. In December 2012, eucalyptus was harvested in Sub-watershed.

Eucalyptus height and leaf area index were obtained from forests inventories carried biannually in circular plots (400 m^2) allocated randomly in eucalyptus stands of all ages (planted in 1990, 2001, 2004, 2005, and 2010). Plant height was measured with a Haglöf Hypsometer and leaf area index was determined by the plant canopy analyzer LAI2000®. The others 37 parameters of Eucalyptus growth were obtained based on growth monitoring in commercial stands in Brazil (Oliveira, 2014) and, afterwards, corrected to climate conditions and inserted into the SWAT database in 2014 (.crop file).

Operations dates vary per year depending on cumulative days exceeding the minimum (base) temperature for plant growth (Bonumá, 2011), and this calculation is particularly important for southern hemisphere conditions. Potential heat units for crops were calculated and values were added to the management input file (.mgt file).

Digital soil map (1:10,000) identifies five soil classes: Ultisols (3), Inceptisol (1) and Planosol (1) (Costa *et al*., 2009). Key soil physical properties such as soil granulometry, bulk density, porosity, and available water were analyzed for each soil and horizon, and the information was added in SWAT user soils databases (.usersoil file).

Soil albedo was determined by the equation (Soil albedo (0.3-2.8 Mm) = 0.69 (color value) - 0.114; $r^2 = 0.93$) proposed by Post *et al*. (2000). Soil erodibility was determined with equation proposed by Denardin (1990) for Brazilian soils ($K = 0.006084\ P + 8.34286\ (10^{-4})\ OM – 1.1616\ (10^{-4})\ Al – 3.776\ (10^{-5})\ CS$), where: K = erodibility (t ha h ha^{-1} MJ^{-1} mm^{-1}); P =

permeability of soil profile (1 - fast; 2 – moderate/fast; 3 - moderate; 4 - slow/moderate; 5 - slow; 6 – very slow); OM = organic matter (g kg^{-1}); Al = Al_2O_3 extracted by sulfuric acid (g kg^{-1}); and CS = coarse sand (0.5-2.0 mm) (g kg^{-1}). Additional soil parameters were taken from a previous study developed in the watershed (Rodrigues, 2011).

The number of HRUs is limited by the precision of input digital maps (Bonumá, 2011). A realistic combination of land uses, soil classes, and slope classes, with a zero (0) percent of threshold area resulted in 151 HRUs and 8 sub-watersheds for Watershed and 48 HRUs and 3 sub-watersheds for Sub-watershed (Figure 3).

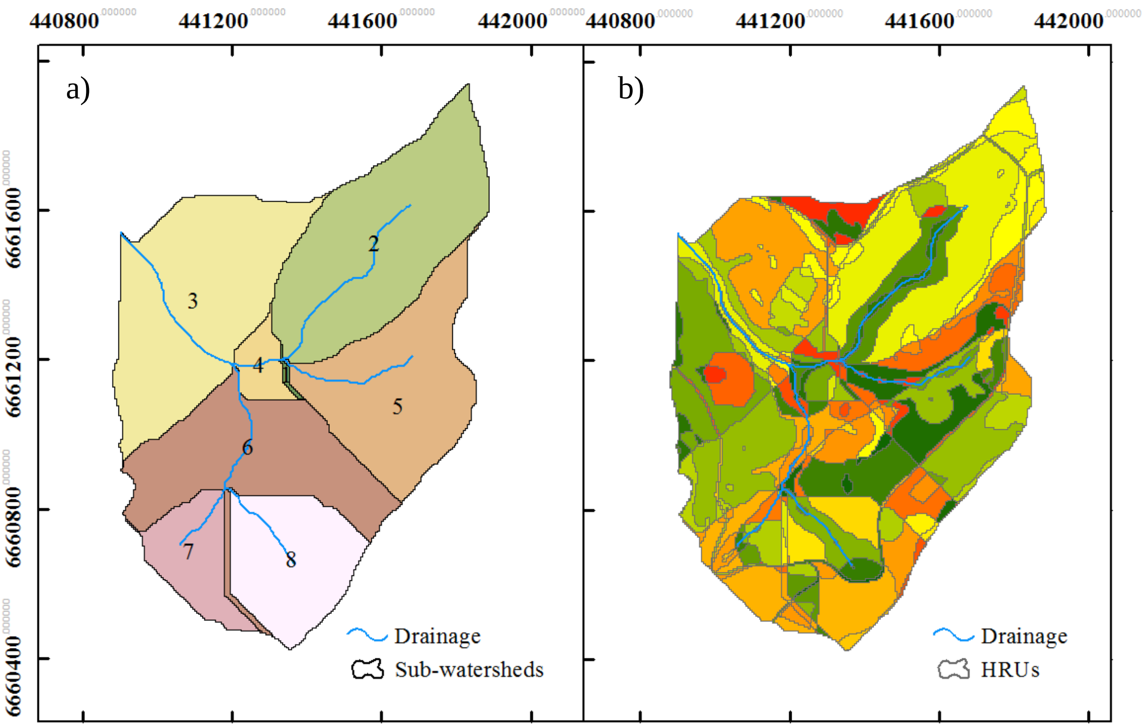

Figure 3. Sub-watersheds (a) and HRUs (b) delineated by the SWAT model, in Eldorado do Sul-RS, Southern Brazil.

Rainfall and climate data were collected and used from 01/01/2009 to 12/31/2013. Rainfall data were obtained from an automatic meteorological station and from an automatic rain gauge installed within the watershed. Climate data were obtained from an automatic meteorological station installed within the watershed, and gaps in climate data were completed with information from the Agronomy Experimental Station of the Federal University Rio Grande do Sul (EEA/UFRGS), located 11 km from the watershed. Climate data from EEA/UFRGS were also used for weather generator input data. Daily maximum and minimum air temperature, solar radiation, wind speed, and relative humidity values were also obtained from the automatic meteorological stations. The Hargreaves-Samani method (Hargreaves & Samani, 1985) was then applied to estimate evapotranspiration and to establish the water balance of each HRU by using the meteorological data. Simulations from 01/01/2009 to 12/31/2013 were performed with SWAT2012, for monthly and daily time-scale, for Watershed and Sub-watershed. The sub-daily time-scale was not used due this option is not available in SWAT2012 version. Rainfall and climate data from 01/01/2009 to 12/31/2010 served as a model parameter value initialization period ("model warm-up"). The outlet gauge data from 01/01/2011 to 12/31/2013 were used for streamflow and sediment yield simulation.

2.2.4 Model calibration

SWAT calibration was performed using the SWAT-CUP software (Abbaspour *et al*., 2007; Arnold *et al*., 2012b). All SWAT parameters can be included in the calibration process (Arnold *et al*., 2012b). Sensitivity analysis and calibration procedure were carried out using 24 parameters of the SWAT model that were suggested as being the most sensitive for streamflow simulation (van Griensven *et al*., 2006; Abbaspour *et al*., 2007) and sediment yield (Abbaspour *et al*., 2007).

The optimization technique used was Sequential Uncertainty Fitting algorithm (SUFI-2) (Abbaspour *et al*., 2007). The SUFI-2 combines optimization with uncertainty analysis and can handle a large number of parameters (Abbaspour *et al*., 2004). The SUFI-2 procedure performs inverse modeling using a sequence of steps in which the initial (large) uncertainties in the model parameters are progressively reduced until reaching a certain calibration requirement based on the prediction uncertainty (Abbaspour *et al*., 2004). The degree to which all uncertainties are accounted for is quantified by a measure referred to as the P-factor, which is the percentage of measured data bracketed by the 95% prediction uncertainty (Abbaspour, 2007). Firstly, an objective function was defined: Nash–Sutcliffe efficiency coefficient greater than 0.5. Thereafter, physically meaningful absolute minimum and maximum ranges for the parameters being optimized was established.

SWAT performance was evaluated using graphical comparison and statistical analysis to determine quality and reliability of predictions when compared to measured monthly and daily streamflow and sediment yield values. We chose as standards for "acceptable" simulations $R^2 > 0.6$ (Bonumá *et al*., 2012, 2013; Santhi *et al*., 2001), NSE > 0.50 and RSR ≤

0.70 for streamflow and sediment, PBIAS ± 25% for streamflow and PBIAS ± 55% for sediment (Moriasi *et al*., 2007) for a monthly time-scale.

When watershed models are evaluated on a daily time-scale the ratings can be less strict than for longer time steps (Moriasi *et al*., 2007). To assess how well the model performed for a daily time-scale, we used Green & van Griensven's (2008) and Wu & Chen's (2009) standards of NSE > 0.4 and $R^2 > 0.5$ as results considered "satisfactory".

Before running the SWAT simulations, the variable datasets were divided into three sub-datasets for initial simulations, as recommended by Arnold *et al*. (2012a): (i) rainfall and climate data from 01/01/2009 to 12/31/2010 were used as a model parameter value initialization ("model warm-up") period to establish appropriate starting conditions for soil water storage; (ii) streamflow and sediment yield data obtained in the outlet gauge from 01/01/2011 to 06/30/2012 were used to optimize the calibration parameters for streamflow and sediment yield; and (iii) streamflow and sediment yield obtained in the outlet gauge from 07/01/2012 to 12/31/2013 were used as validation parameters for streamflow and sediment yield.

Since an "acceptable" simulation of streamflow and sediment yield in the watershed outlet during calibration phase did not provide a good performance during validation phase of runoff generation processes in the watershed after the initial simulations, variable datasets were, therefore, divided into only two sub-datasets: one for model warm-up (01/01/2009-12/31/2010), and another to optimize calibration parameters for streamflow and sediment yield (01/01/2011-12/31/2013) for monthly and daily time-scale, for both Watershed and Sub-watershed.

2.3 Results

2.3.1 Sensitivity analysis

Parameter sensitivity on monthly time-scale was different between Watershed and Sub-watershed for most parameters (Figure 4). For streamflow and sediment yield, in both Watershed and Sub-watershed, soil hydraulic conductivity (SOL_K) was the most sensitive parameter. Subsequently the SOL_K sensitivity analysis for Watershed showed the most sensitive parameters to both variables, in descending order, were available water capacity of soil (SOL_AWC); soil evaporation compensation factor (ESCO); effective hydraulic conductivity in the main channel alluvium (CH_K2); Manning's roughness coefficient value for the main channel (CH_N2); biological mixing efficiency (BIOMIX); maximum canopy storage (CANMX); initial SCS runoff curve number for moisture condition II (CN2);

baseflow recession constant (ALPHA_BF); maximum potential leaf area index for land cover/plants (BLAI); groundwater “revap” coefficient (GW_REVAP); plant uptake compensation factor (EPCO); groundwater delay (GW_DELAY); deep aquifer percolation fraction (RCHRG_DP); moist soil albedo (SOL_ALB); depth to bottom of soil layer n (SOL_ZMX); surface runoff lag time (SURLAG); threshold depth for return flow of water in the shallow aquifer (GWQMIN); and threshold depth for “revap” of water in the shallow aquifer (REVAPMN) (Figure 4a). Sensitivity analysis for Sub-watershed showed the most sensitive parameters for all variables were GWQMIN, ALPHA_BF, EPCO, GW_DELAY, RCHRG, SOL_Z, CN2, SURLAG, ESCO, CANMX, SOL_AWC, CH_K2, SOL_ALB, GW_REVAP, BIOMIX, REVAPMN, CH_N2, BLAI, in descending order (Figure 4b).

For sediment in Watershed, sensitivity analysis showed the most sensitive parameters were, in descending order, the USLE equation support practice factor (USLE_P), even considering the absence of management practices during the eucalyptus cycle and the soil protection effect provided by eucalyptus stands compared to agricultural land use and intensity tillage practices; the linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing (SPCON); the exponent parameter for calculating sediment re-entrained in channel sediment routing (SPEXP); and the channel cover factors (CH_COV1 and CH_COV2) (Figure 4a). Sensitivity analysis for Sub-watershed showed that the most sensitive parameters were SPCON, USLE_P, SPEXP, CH_COV1 and CH_COV2, in descending order (Figure 4b).

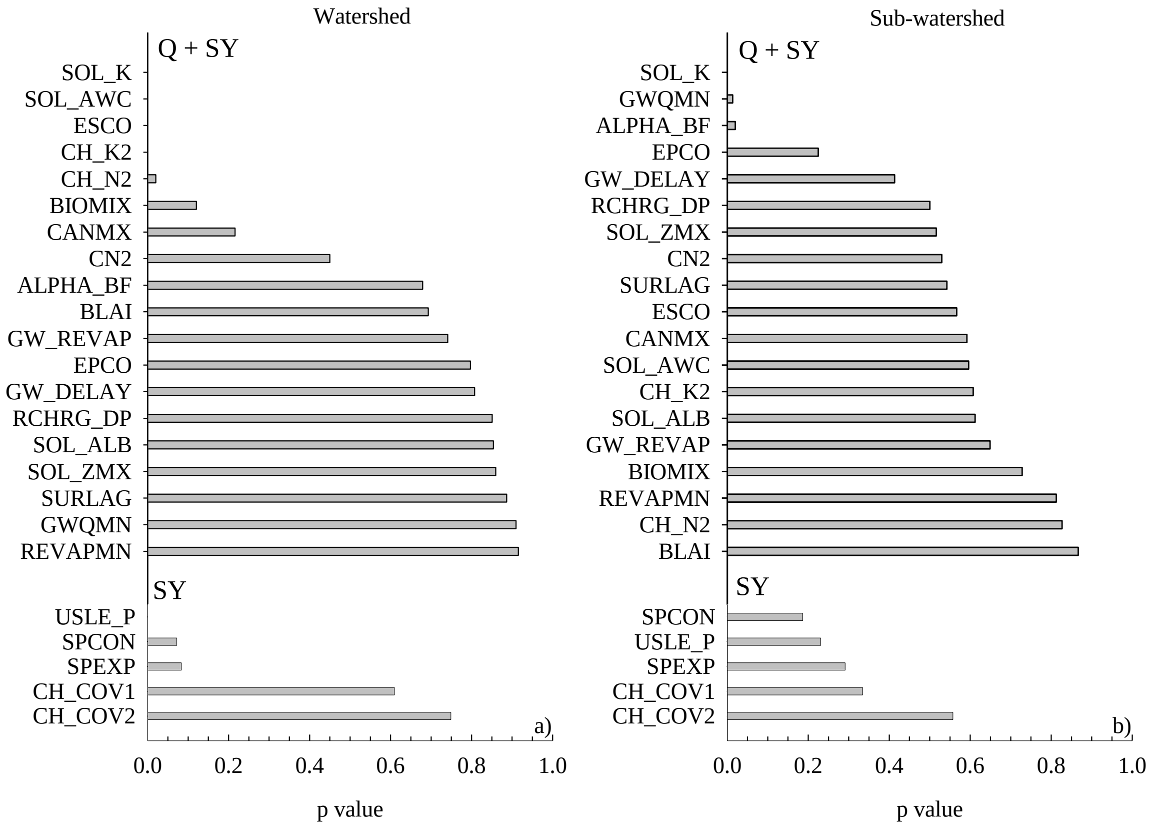

Figure 4. Sensitive parameters on monthly time-scale for streamflow and sediment yield (Q + SY) and for sediment only (SY) for Watershed (a) and Sub-watershed (b).

Parameter sensitivity was different between Watershed and Sub-watershed for most parameters on daily time-scale evaluation (Figure 5). For streamflow and sediment yield CH_N2 and SOL_K were the two most sensitive parameters in Watershed (Figure 5a), while for Sub-watershed the most sensitive parameters were CH_K2, ALPHA_BF, SOL_K and EPCO, in descending order (Figure 5b); the other parameters had low sensitive. Furthermore, for sediment yield in both Watershed and Sub-watershed parameters were not sensitive (Figure 5).

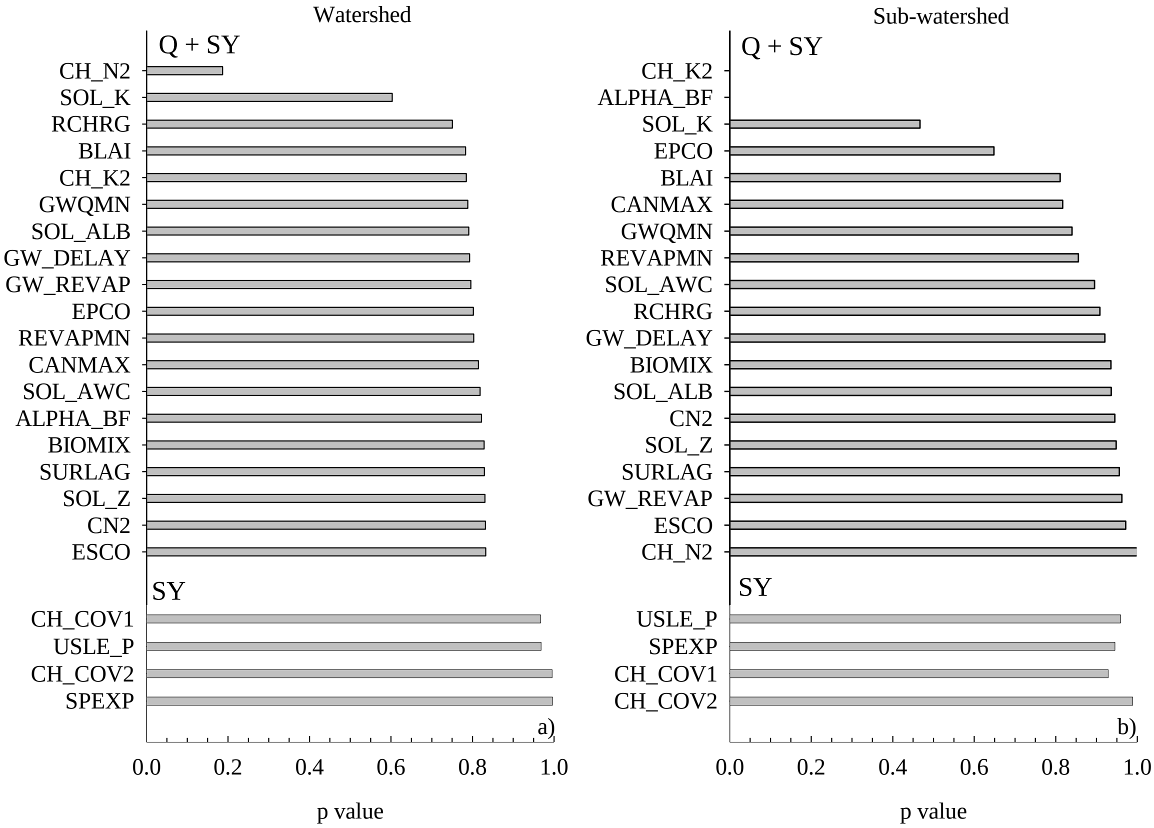

Figure 5. Sensitive parameters on daily time-scale for streamflow and sediment yield (Q + SY), and for sediment only (SY) for Watershed (a) and Sub-watershed (b).

2.3.2 Monthly streamflow and sediment yield

Monthly observed and simulated streamflow matched well during the calibration period for both Watershed and Sub-watershed (Figure 6). Model performance to represent streamflow was “very good” for the calibration period for both Watershed and Sub-watershed, following the classification proposed by Moriasi *et al*. (2007): for Watershed, NSE of 0.97 (> 0.75), RSR value of 0.17 (≤ 0.50), and PBIAS of 1.3% (modular value < 10%); while for Sub-watershed NSE of 0.83 (> 0.75), RSR value of 0.41 (≤ 0.50), and PBIAS of 8.6% (modular value < 10%). Monthly calibration R^2 values were 0.97 and 0.84 (> 0.6) for Watershed and Sub-watershed, respectively (Figure 7), which are considered to be “acceptable”.

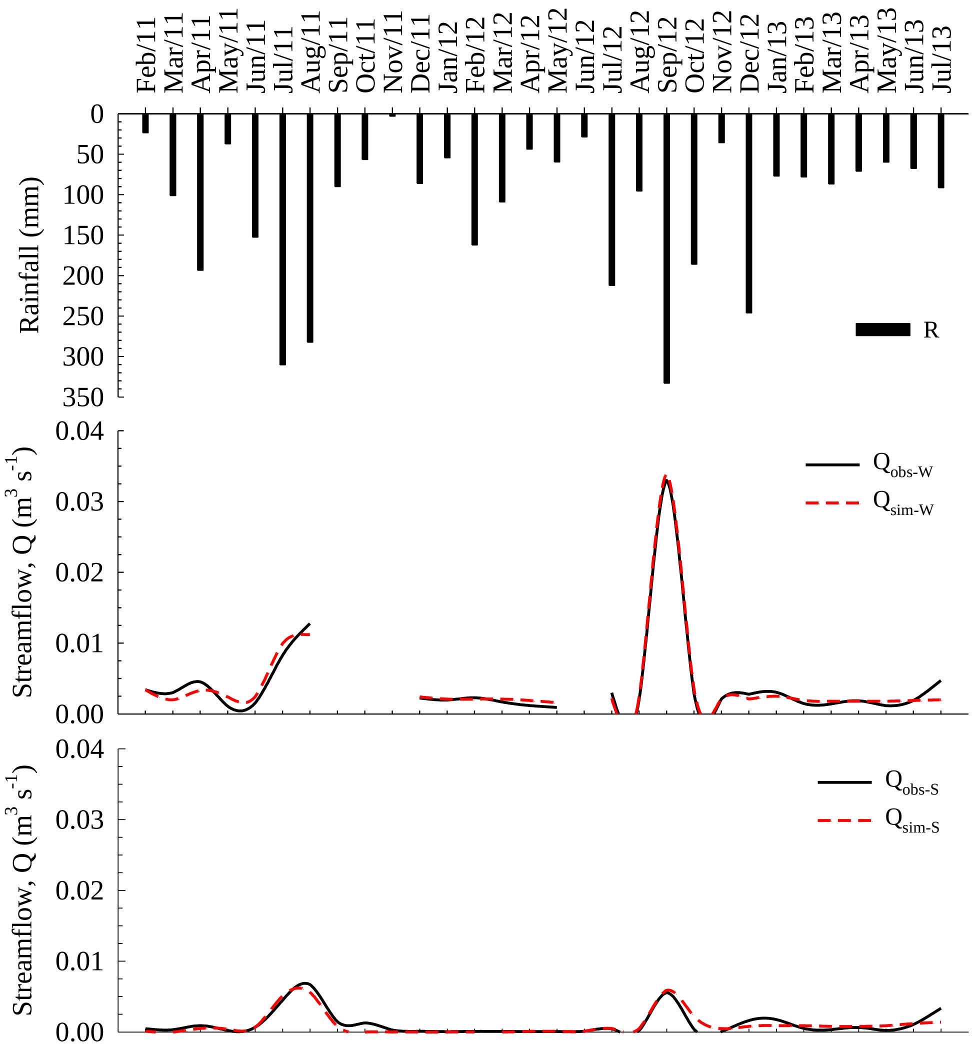

Figure 6. Monthly rainfall (R), and observed and simulated streamflow for Watershed ($Q_{obs\text{-}W}$ and $Q_{sim\text{-}W}$) and for Sub-watershed ($Q_{obs\text{-}S}$ and $Q_{sim\text{-}S}$) outlets.

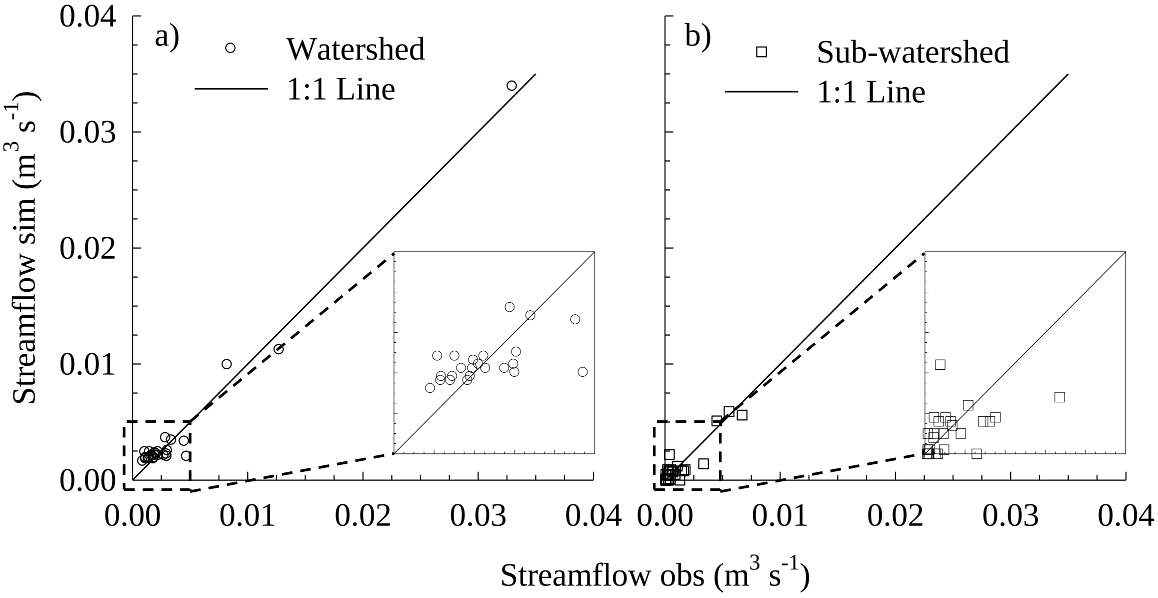

Figure 7. Monthly dispersion diagram of observed and simulated streamflow for Watershed (a) and Sub-watershed (b) (zoom at 0.005 $m^3 s^{-1}$). *Sim: simulated; Obs: observed.

Monthly observed and simulated sediment yield matched well during the calibration period only for Watershed, where sediment yield was underpredicted by about 36% (Figure 8). For Sub-watershed, statistical indicators were "unsatisfactory", namely NSE ≤ 50, RSR > 70, and PBIAS ≥ 55% (modular value).

Monthly calibration R^2 were 0.92 (> 0.6) for Watershed (Figure 9), which is considered "acceptable". Model performance for sediment yield was "very good" for Watershed during the calibration period, supported by an NSE of 0.90 (> 0.75) and an RSR value of 0.32 (≤ 0.50), but based on the PBIAS of 36.2% performance was "satisfactory" (modular value 30 ≤ PBIAS ≤ 50%).

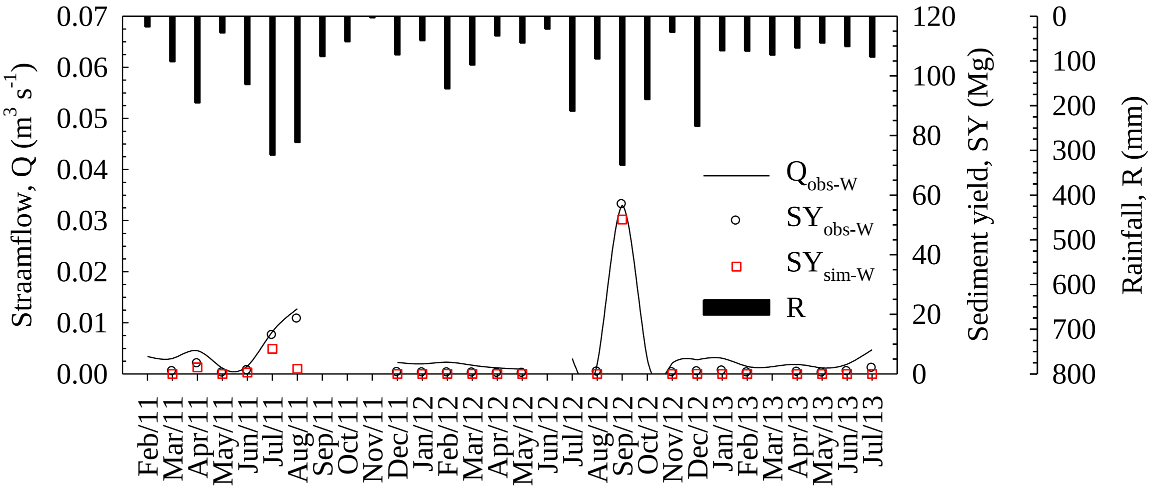

Figure 8. Monthly rainfall (R), observed streamflow (Q_{obs-W}), and observed (SY_{obs-W}) and simulated (SY_{sim-W}) sediment yield for Watershed outlet.

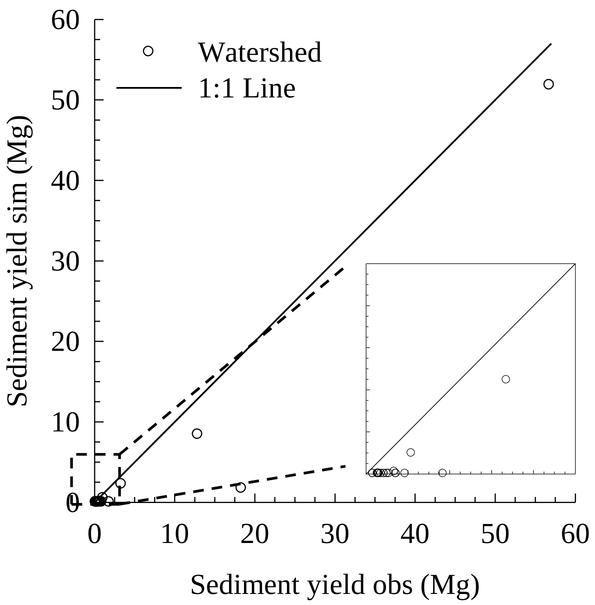

Figure 9. Monthly dispersion diagram of observed and simulated sediment yield for Watershed (zoom at 5 Mg). *Sim: simulated; Obs: observed.

2.3.3 Daily streamflow and sediment yield

Daily observed and simulated streamflow matched well only during the calibration period for Watershed and Sub-watershed (Figures 10 and 11). Statistical indicators for Watershed (NSE = 0.80 and R^2 = 0.80) and for Sub-watershed (NSE = 0.47 and R^2 = 0.73) were “satisfactory” according to our chosen standards (NSE > 0.4 and R^2 > 0.5). Streamflow was underpredicted for some periods and overpredicted for other periods, for both Watershed and Sub-watershed. A trend of underprediction of peak flows and overprediction of streamflow for hydrograph recession simulation was observed for both Watershed and Sub-watershed (Figure 12).

Statistical parameters observed for streamflow on daily time-scale for Watershed were high (NSE = 0.80, PBIAS =-1.90, and RSR = 0.45). If we consider that the Moriasi et al. (2007) is also valid for monthly time-scale, these parameters are classified as “very good”, where for Sub-watershed the parameters on a daily time-scale (NSE = 0.47, PBIAS =-57.50, and R2 = 0.73) were less than those considered “unsatisfactory”.

Model performance for daily sediment yield was “satisfactory” for Watershed during the calibration period, supported by an NSE of 0.55 (> 0.40) and an R^2 of 0.55 (> 0.50), even though sediment yield had been underpredicted on most days (Figure 13). However, these “satisfactory” statistical indicators for sediment yield prediction were obtained because few events with high sediment yield occurred in Watershed, which not represent the erosive processes occurring in the Watershed. Daily sediment yield calibration for Sub-watershed was “unsatisfactory”, because NSE was 0.37 (< 0.40), even though R^2 was 0.67 (> 0.50).

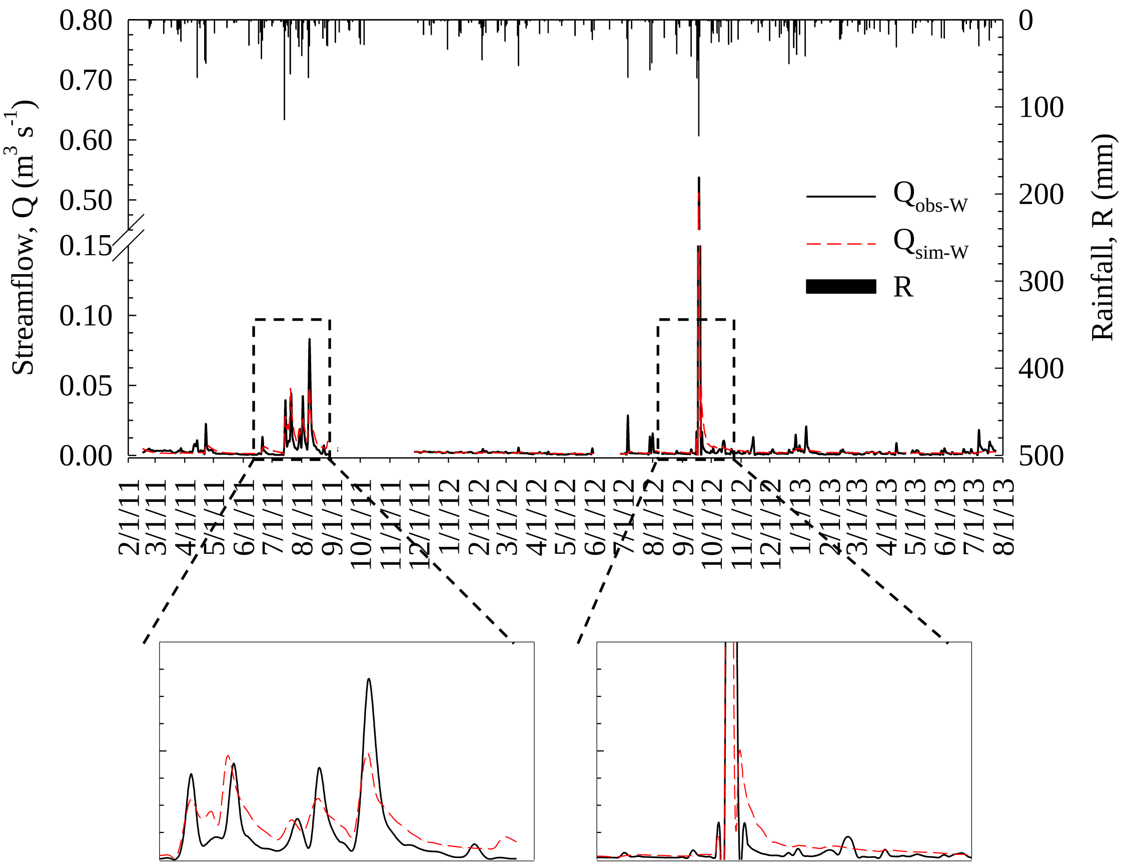

Figure 10. Daily rainfall (R), and observed and simulated streamflow for Watershed ($Q_{obs\text{-}W}$ and $Q_{sim\text{-}W}$) outlet (zoom at 0.10 m^3 s^{-1}).

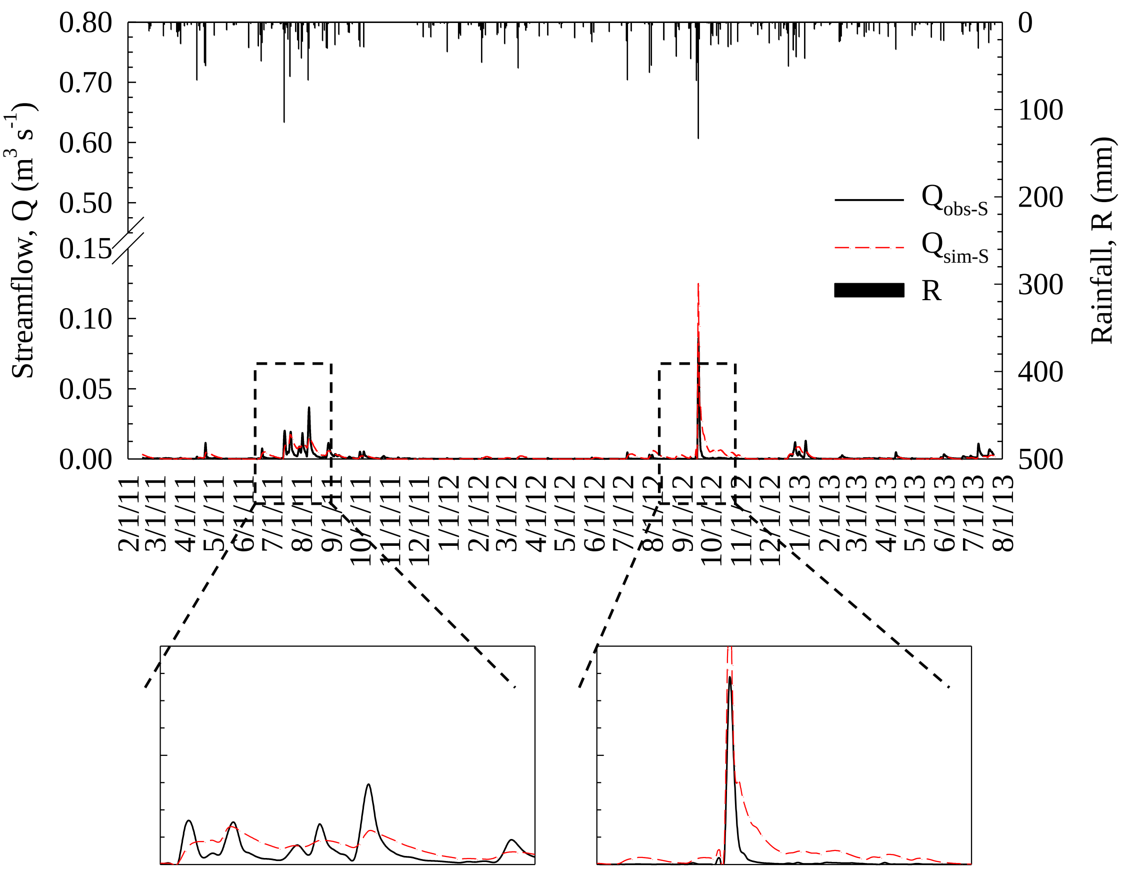

Figure 11. Daily rainfall (R), and observed and simulated streamflow for Sub-watershed (Q_{obs-S} and Q_{sim-S}) outlet (zoom at 0.10 m^3 s^{-1}).

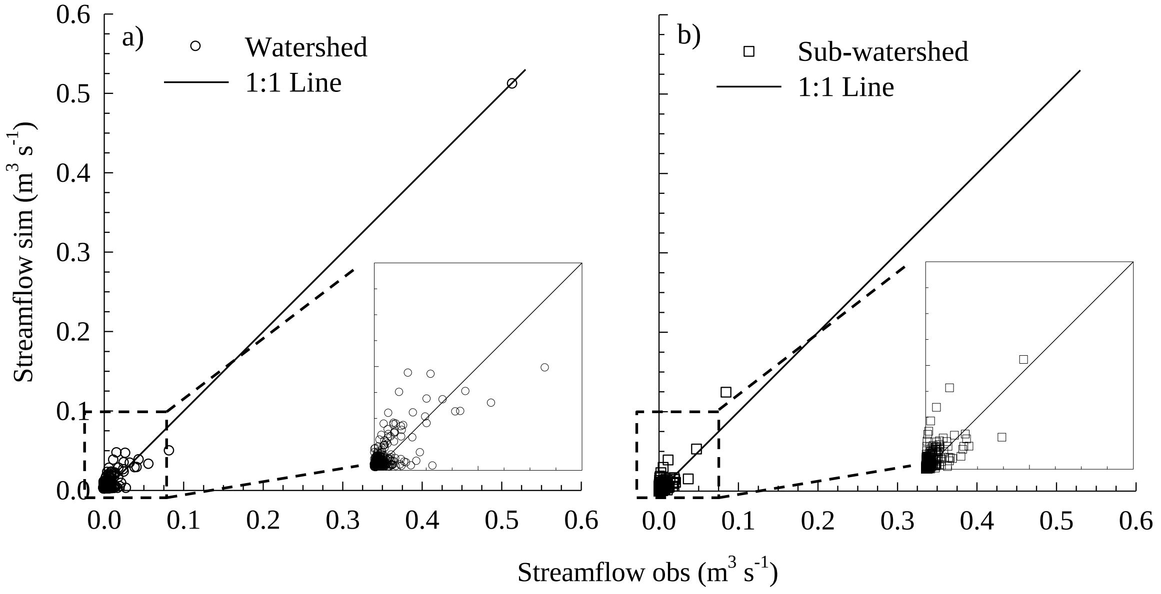

Figure 12. Daily dispersion diagram of observed and simulated streamflow for Watershed (a) and Sub-watershed (b) (zoom at 0.1 m^3 s^{-1}). *Sim: simulated; Obs: observed.

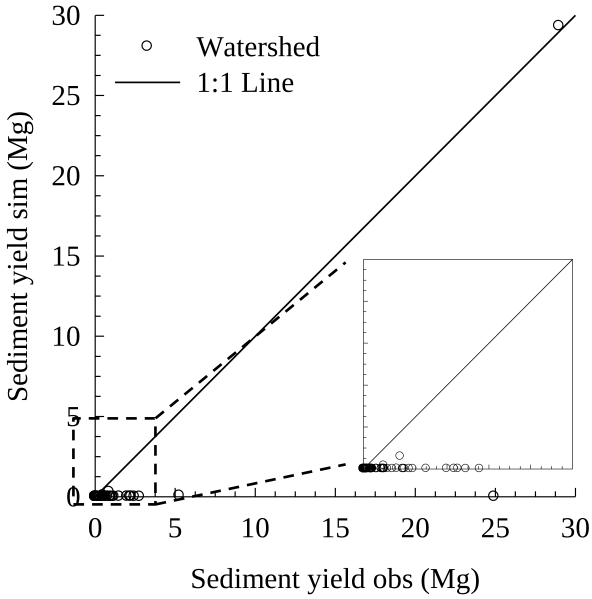

Figure 13. Daily dispersion diagram of observed and simulated sediment yield for Watershed (zoom at 5 Mg). *Sim: simulated; Obs: observed.

2.3.4 Hydrologic and soil erosion balance

Average annual values for hydrologic balance, such as surface runoff, lateral runoff, groundwater contribution to streamflow (return flow), percolation to shallow aquifer, soil water storage, evapotranspiration, and water yield, were obtained from SWAT outputs (Figure 14) and compared to calculated values, based on rainfall and streamflow measurements in the Watershed and Sub-watershed outlet gauges. The hydrologic balance are explained since we observed agreement between monthly measured and simulated streamflow values was achieved during calibration period at the Watershed and the Sub-watershed, supported by statistical indicators.

Potential evapotranspiration (PET), 1187.8 mm for both the Watershed and sub-watershed, computed by the SWAT model were corrected for soil land use, on the basis of simulated plant growth, to give actual evapotranspiration (ET) (846.7 mm), for both Watershed and Sub-watershed. The results indicated that 57% of the annual rainfall is lost by ET in the Watershed and in the Sub-watershed, according to SWAT calibrated values.

According to SWAT simulation results, the surface runoff contributes for the Watershed and the Sub-watershed, respectively, 7% and 1%; the groundwater contributes 16% and 6%; and the lateral flow contributes about 6% and 14% of the water yield.

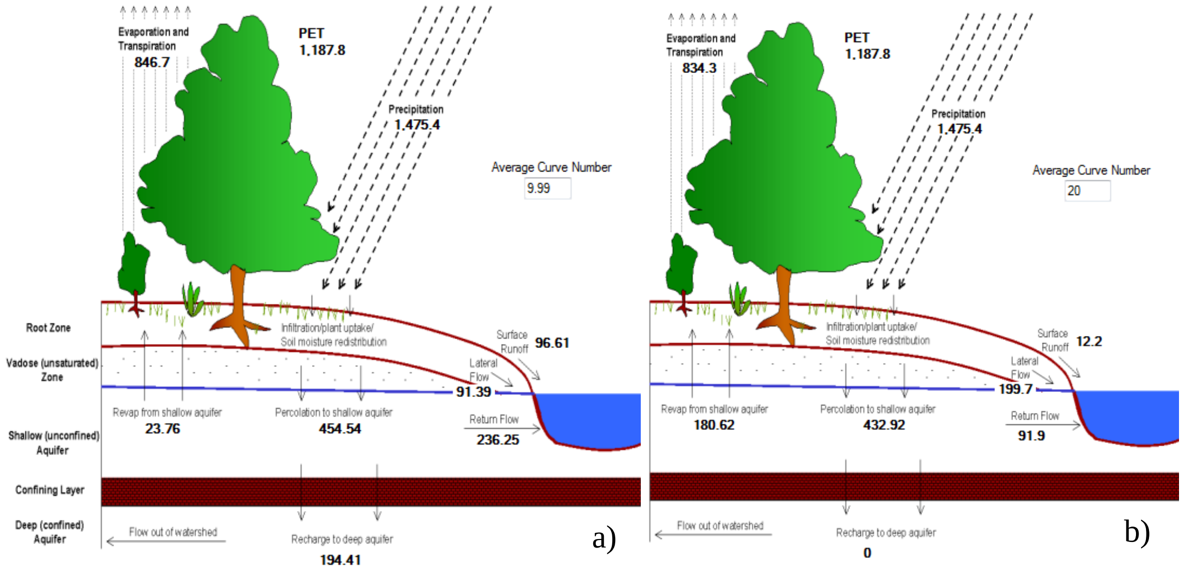

Figure 14. Calibrated annual-average hydrologic processes in the water balance (SWAT output) for the Watershed (a) and for the Sub-watershed (b), in Eldorado do Sul-RS, Southern Brazil.

Although the SWAT model was effective in simulating monthly and daily sediment yield in Watershed, based on “satisfactory” statistical indicators, adequate spatially sediment yield representation was not observed. SWAT model output indicated that sub-watersheds with steeper gradient seem to generate more sediment yield (Table 1; Figure 15).

Table 1. Calibrated annual sediment yield (Mg) (SWAT output) in the sub-watersheds delineated by SWAT for the Watershed.

Sub-watersheds SWAT delineated by SWAT	Sediment yield (Mg)		
	2011	2012	2013
Watershed			
1	0.00000000	0.00000000	0.00000000
2	0.00000546	0.00000548	0.00000546
3	0.00000000	0.00000000	0.00000000
4	0.00000000	0.00000000	0.00000000
5	0.00001090	0.00001100	0.00001090
6	0.00000000	0.00000000	0.00000000
7	0.00000729	0.00000731	0.00000729
8	0.00000620	0.00000621	0.00000620

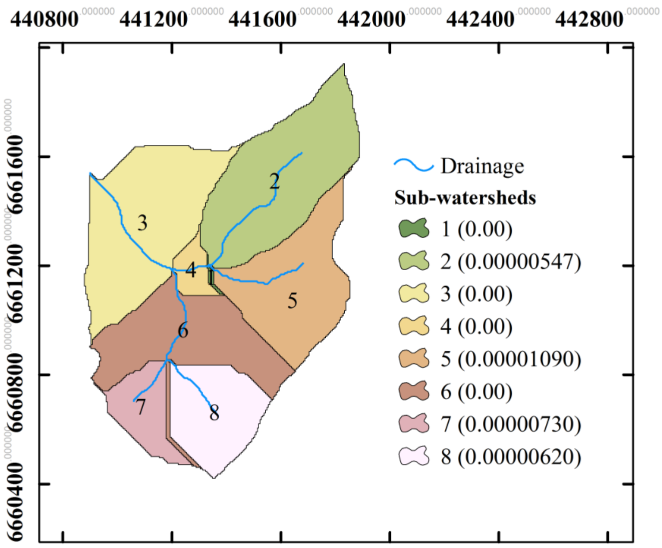

Figure 15. Calibrated annual-average sediment yield (Mg) (SWAT output) in the sub-watersheds delineated by SWAT, for the Watershed, in Eldorado do Sul-RS, Southern Brazil.

2.4 Discussion

2.4.1 Sensitivity analysis

The sequence of parameters for sensitivity was different between Watershed and Sub-watershed. Soil saturated hydraulic conductivity (SOL_K), the most sensitive parameter for both watersheds, is not the most sensitive parameter for most studies using SWAT (Lelis *et al.*, 2012). However, parameters must be sensitive and represent the processes occurring in the area under study. In studies conducted by Schmalz & Fohrer (2009) and Fukunaga *et al.* (2015), the most sensitive parameters were the groundwater parameters, ponds and wetlands, soil, drainage and surface runoff.

The SOL_K parameter is related to infiltration and runoff processes, and changes in SOL_K have an effect on streamflow and, subsequently, on sediment yield. However, the water balance for the shallow aquifer considers water stored in the shallow aquifer, aquifer recharge, and groundwater or base flow. Recharge is defined by the amount of recharge entering the aquifer, the total amount of water exiting the bottom of the soil profile, and the delay time of the overlying geologic formations (GW_DELAY). A fraction of the total daily recharge can be routed to the deep aquifer. The amount of water moving from the shallow aquifer due to percolation into the deep aquifer is correlated to the aquifer percolation coefficient (RCHRG_DP) and the amount of recharge entering both aquifers (Neitsch *et al.*, 2005; Arnold *et al.*, 2012b). Shallow aquifer contributes for baseflow to the main channel or to the reach within the sub-watersheds. Baseflow is allowed to enter the reach only if the amount of water stored in the shallow aquifer exceeds a threshold value specified by the user GWQMN, as observed in the Sub-watershed. The baseflow recession constant (ALPHA_BF) is a direct index of groundwater flow response to changes in recharge (Arnold *et al*., 2012b).

SWAT models the movement of water into overlying unsaturated layers as a function of water demand for evapotranspiration, and this process is significant in watersheds where the saturated zone is not very far below the soil surface. The maximum amount of water that will be removed from the aquifer by re-evaporation is correlated by the re-evaporation coefficient (GW_REVAP) and the potential evapotranspiration (Neitsch *et al*., 2005; Arnold *et al*., 2012b). These parameters indicate that water flow in this lowland region is dominated by infiltration, percolation and baseflow due to shallower soil and proximity to the shallow groundwater, and by lateral flow due to impedance soil layers in Sub-watershed. This behavior in water flow is consistent for Sub-watershed because the smaller drainage area and steeper relief provide faster soil saturation during several rainy days and water recharge of the shallow aquifer, which provide high potential for lateral flow (Rodrigues *et al*., 2014).

For Watershed, groundwater parameters were less sensitive than observed for Sub-watershed. Besides the effects of the soil SOL_K parameter, other parameters related to soil (SOL_AWC and ESCO), management (BIOMIX), channel (CH_K2 and CH_N2), and surface runoff (CANMX and CN2) were most sensitive. For a Brazilian watershed (2.84 km^2) with eucalyptus as the major land use, Oliveira (2014) observed that CN2, CANMX, CH_K2, ALPHA_BF, SURLAG, ESCO, and CH_N2 were the most sensitive parameters, which is similar to our findings.

Reduction in SOL_K and increase in SOL_AWC parameters during the calibration resulted in lower water infiltrated and soil water storage retained with low energy in the soil, thus providing an increasing in surface runoff and maximum peak flow, which is in agreement with results obtained by Fukunaga *et al*. (2015). Reduction in CANMX contributes to reduce the initial abstractions, and helps to reduce surface runoff and peak flow. Sensitivity for CANMX was also observed by Lelis *et al*. (2012) in sub-watersheds covered with forest.

Results indicate that the processes are sensible to soil, land use, and topography parameters that exert control to watershed system and physical properties of the watersheds through the SWAT model (Schmalz & Fohrer, 2009; Lelis *et al*., 2012), which are dependent on watershed size. For small areas, as at the field scale, water balance processes include many variables that are interdependent with other processes, such as plant growth, soil properties, and weather. Field-scale models often simulate the main hydrological and biogeochemical processes, including infiltration and soil water distribution in the vadose zone, evapotranspiration, subsurface drainage, surface runoff, soil erosion, sediment transport, and plant growth, for one or more plots or fields (Arnold *et al*., 2015). For large-scale watershed models simulate complex hydrologic processes on a watershed or basin scale, in addition to the processes occurred in each plot, field or sub-watersheds that compose the main watershed. These processes include parameters related to ditch/channel/riparian and reservoir processes, erosion and sediment movement and deposition, water/air interactions, complex soil/plant/climate interactions, and cycling in floodplains and wetlands (Arnold *et al*., 2015). This is in agreement with our study, where parameters related to channel processes are most sensibility in the watershed, mainly on monthly time-scale.

On a daily time-scale, soil (SOL_K) and channel (CH_N2) parameters were the most sensitive parameters for Watershed, meaning the increase in daily streamflow in Watershed depends of the reduction in SOL_K and in CH_N2, which resulted in lower water infiltration, higher runoff, lower impediment of channel flow, and, consequently, higher flow velocity in the main channel. For Sub-watershed, on daily time-scale, an increase in effective hydraulic conductivity in the main channel alluvium (CH_K2), an increase in baseflow recession constant (ALPHA_BF), and an increase in soil hydraulic conductivity (SOL_K) provide higher groundwater flow response. Furthermore, with a reduction in the EPCO parameter, removal of water from the soil by plants is higher than the system capacity to compensate for removal. These results indicate parameter sensibility on daily time-scale for Sub-watershed is affected by soil, topography, and other physical properties of the watersheds, which are dependent on watershed size, similar to Watershed.

2.4.2 Streamflow

Monthly observed and simulated streamflow matched well for the calibration period, where representation of streamflow was considered “very good” (Moriasi *et al*., 2007) for both Watershed and Sub-watershed. Our results were better than those observed by Oliveira (2014) in a forest watershed cultivated with eucalyptus stands, where calibration was considered “satisfactory”. However, streamflow statistical indicators were greater for monthly than daily time-scale for both Watershed and Sub-watershed; representations of streamflow on monthly time-scale were considered to be “very good” (Moriasi *et al*., 2007).

Monthly streamflow is best represented in comparison to daily streamflow because the former considers the total amount accumulated in the month, disregards conditions occurring over a few days, combines dry periods with periods of high rainfall across the month, and does not show whether rains were well distributed throughout the month. However, when the simulation is performed on daily time-scale, there is discretization of the total volume accumulated in the month, and rainy and dry days are clearly presented, which provides the evidence of dry spells and reduces the ability of the model to represent the processes on daily time-scale. Then, the use of SWAT model for water processes simulation in a daily time-scale, even that statistical indicators were considered "acceptable", should be used with caution or not be used for small watershed where the water processes occurring in less than one day, which indicate that simulations need to be performed in the sub-daily time scale to adequately represents the water processes.

SWAT seems to simulate wet periods better than dry periods (Green *et al*., 2006; Setegn *et al*., 2010; Qiu *et al*., 2012; Bonumá *et al*., 2013), possibly because of the inclusion of a larger number of rainfall events which tend to minimize variability with greater time-scales (Bonumá *et al*., 2013). Additionally, model simulations probably could not capture runoff peaks for daily flow events due to the uncertainty in the modified Soil Conservation Service curve number (CN2) method used for predicting surface runoff from daily rainfall (Mishra & Singh, 2003; Bonumá *et al*., 2013). Uncertainty in estimated surface runoff from daily rainfall is greater when time of concentration of the watershed is less than one day (Uzeika *et al*., 2012), as the ones of our study. Since one value represents the range of rainfall intensities that can occur within a day, uncertainties may exist within the time period that are not captured (Green *et al*., 2006). Similar to our study, Bonumá *et al*. (2013) observed underprediction for low flows on daily time-scale due to inadequacy of the hydrograph recession simulations, partly due to measurement errors.

Underprediction of peak flows and overprediction of hydrograph recession occurs because peak flows are more sensitive to variations due to rainfall intensity (Green *et al*., 2006) and to antecedent soil moisture content (Moriasi *et al*., 2007), while the recession curves are affected by the baseflow component (Bonumá *et al*., 2013). Considering these uncertainties, it is necessary to simulate the processes in the time-scale in which they occur, especially in small watersheds where the processes occur in only a few hours.

Model performance to represent streamflow was better for Watershed than for Sub-watershed, based on the statistic rating suggested by Moriasi *et al*. (2007). Since SWAT was developed to evaluate the effects of alternative management decisions on water resources and nonpoint-source pollution in large river basins (Arnold *et al*., 2012a), SWAT performance is expected to decrease when the scale of analyses decreases. "Satisfactory" model performance at a gauge does not guarantee plausible results at smaller areas (Bieger *et al*., 2015), such as at the sub-watersheds and the HRU level. For a small watershed (8.27 km^2), Qiu *et al*. (2012)

observed a tendency of the model to underpredict runoff in wet seasons, and overpredict in dry seasons. In nested watersheds with native forest, Meaurio *et al*. (2015) observed that a small sub-watershed (1.0 km^2) provided the greater uncertainties in modeling compared to a larger watershed (4.6 km^2). They observed that underprediction of peak flows in the sub-watershed, as observed in our study, had a direct effect on simulation of watershed outlet discharge, and therefore had the largest errors and uncertainties for the smaller area.

Therefore, as shown above, SWAT needs improvement to simulate processes for forested small and nested watersheds. The physical properties (size, relief, soil type) of sub-watersheds (Meaurio *et al*., 2015) affect hydrosedimentological processes in the watershed, and the limited knowledge about these properties may reduce performance of the SWAT model especially for daily time step (Bonumá *et al*., 2013). Uncertainty due to input data scarcity and short period of monitored data affect model parameter values (Bonumá *et al*., 2013). If a parameter value does not adequately represent a process, negative effects are expected for surface and baseflow processes.

Hence, the greatest uncertainties related to modeling of nested watersheds with the SWAT model derive from the spatial distribution of streamflow, specifically in smaller sub-watersheds (Meaurio *et al*., 2015). Probably for this reason Bieger *et al*. (2015) highly recommend evaluation of the model output for small areas.

2.4.3 Sediment yield

The model was effective in simulating monthly and daily sediment yield in Watershed, based on “satisfactory” statistical indicators. During the studied period, SWAT model simulation of Watershed showed that sediment yield was underpredicted for most periods for both monthly and daily time-scales. “Satisfactory” statistical indicators for sediment yield prediction were obtained because few events with high sediment yield occurred in Watershed, but this behavior of “satisfactory” statistical indicators for sediment yield prediction does not represent the erosive processes occurring in the Watershed. SWAT did not accurately represent sediment yield in dry periods with low sediment yield, which is possibly related to low sediment delivery ratio in each channel (Rodrigues *et al*., 2014) and indicates that in-stream erosion/sedimentation might be of high importance in our studied watershed.

Studies using the SWAT model for small watersheds have been conducted in watersheds where agriculture is the major land use. Thus, our results were compared to results obtained in small agricultural watersheds in Southern Brazil, by Uzeika *et al*. (2012) and Bonumá *et al*. (2013). We obtained “satisfactory” statistical indicators for sediment yield prediction, contrary to the findings of Uzeika *et al*. (2012) and Bonumá *et al*. (2013). These two studies observed overpredicted sediment yields using the SWAT model. Uzeika *et al*. (2012) obtained “unsatisfactory” results, where the SWAT model was not able to predict daily and monthly sediment yields adequately for each evaluated year, and the SWAT model significantly overpredicted sediment yield for both time-scales for a small watershed (1.19 km^2).

Initial simulation made by Bonumá *et al*. (2013) in a small agricultural watershed (4.8 km^2) resulted in sediment yield overprediction, and the statistical indicator was “unsatisfactory” (PBIAS = − 190%). Even after calibration of sensitive parameters for sediment yield, simulated sediment yield was excessively high compared with observed values, and the PBIAS was − 84%. They introduced a new sediment routine into the SWAT model that integrates landscape transport capacity of sediments and sediment deposition routines, where results increased accuracy in steeper areas while significantly improving its ability to predict the spatial distribution of sediment deposition areas.

Unfavorable simulation results for agricultural watersheds may be caused by either limitations of the sediment load equation (MUSLE) or sediment propagation in channels. Sediment deposition was held responsible for the overprediction of sediment yield since large volumes of sediment were deposited in depressions in fields near to alluvial channels, thus indicating that not all eroded soil on hillslopes reached the stream (Uzeika *et al*., 2012; Bonumá *et al*., 2013; Bonumá *et al*., 2015).

Our results indicate underpredicted sediment yields. SWAT’s underprediction of sediment load could be attributed to its dependence on many empirical and semi-empirical models, such as SCS-CN and MUSLE, which causes SWAT to track specific peak runoff and sediment load less accurately. These findings have implications for modifying the model to take the rainfall intensity and its duration into account to enhance model accuracy for peak flow and sediment load simulation when the model is applied to flood prediction (Qiu *et al*., 2012).

2.4.4 Hydrologic and soil erosion balance

Actual evapotranspiration for both Watershed and Sub-watershed (57% of the annual rainfall) according to SWAT calibrated values agree with evapotranspiration observed in studies conducted in a eucalyptus watershed. In two studies conducted in two different watershed covered with eucalyptus in a Pampa Biome, Southern Brazil, Baumhardt (2014) and Peláez (2014) found, respectively, that 72% and 50% of the precipitation is lost by evapotranspiration; results obtained by Peláez (2014) are close to our results.

Low surface runoff simulated by SWAT is coherent with observed by Rodrigues *et al*. (2014), and this behavior occurs due the eucalyptus stands provided protection for the soil surface by trees and litter interception.

Lateral flow is a considerable portion of total flow and indicates the presence of a restrictive layer below the soil surface or possibly an overestimation of lateral flow (Bonumá *et al*., 2013). The lateral flow is calculated simultaneously with percolation using a kinematic storage routing technique that is based on slope, slope length, and saturated hydraulic conductivity (Arnold *et al*., 2000). High intensity rainfall, in addition to shallow and stony soils located on steeper slopes in the watershed, can contribute to a higher lateral flow since the water was more likely to move laterally than vertically (Bonumá *et al*., 2013). Combined, these factors result in faster soil saturation during rainfall, which increases surface runoff and also increases water flow in the soil. Flow may progress over the impermeable layer, especially in soils with higher surface saturated hydraulic conductivity compared to that of the lower layers (Bonumá *et al*., 2013). Since baseflow parameters may be subject to considerable uncertainty due to the lack of direct measurements, the calibrated model can be considered to generate “acceptable” predictions of baseflow (Bonumá *et al*., 2013).

As the SWAT model produced adequate simulation results for monthly and daily time-scale, the model can produce reasonable estimates of the different components of hydrological balance provided the model user has knowledge of realistic watershed-parameter input values. SWAT model simulations evidenced that baseflow is an important component of the total water yield within the study area and accounts for greater flow than the surface runoff component, as also observed by Bonumá *et al*. (2013).

Even though SWAT model produce reasonable estimates of the different components of hydrological cycle and adequate streamflow simulation for monthly and daily time-scale, when we analyze spatially sediment yield we observed adequate streamflow representation does not means adequate spatial sediment yield representation. The sediment loss in our study is likely more affected by land management practices than by slope, and from field observations the main erosion process occurs in the stream channel.

Thus, absence of management practices during the eucalyptus cycle and soil protection provided by eucalyptus stands, compared to agricultural land use with intense tillage practices, and the low effect of erosion processes in stream channel considered in SWAT model simulation may have contributed to sediment yield underprediction. However, SWAT model output indicated that sub-watersheds with steeper gradient seem to generate more sediment yield (Table 1; Figure 15), and the erosion channel processes seem low, because field experience shows that stream channel in sub-watersheds 1, 2, 4 and 5 have high contribution to erosion in the Watershed.

2.5 Conclusions

The SWAT ecohydrological model provided good results for the simulation of streamflow for forested nested small watersheds. SWAT provided better results for monthly time-scale than for daily time-scale. Model simulations could not capture runoff peaks well for daily flow events, probably due to the uncertainty in the method used for estimating surface runoff from the daily rainfall. The model tended to overpredict streamflow during hydrograph recession simulations.

SWAT was efficient in predicting sediment yield for monthly and daily time-scales for Watershed, but not for Sub-watershed. Sediment yield was underpredicted, possibly due to model dependence upon empirical and semi-empirical equations, which do not represent the physical processes and caused SWAT to track specific peak runoff and sediment load less accurately. Absence of management practices during the eucalyptus cycle and the soil protection effect provided by eucalyptus stands, compared to agricultural land use and intensity tillage practices, may have contributed to sediment yield underprediction for the model.

More field work is required in order to understand the hydrology and sedimentology behavior of spatial and temporal variations, in small forested watersheds and sub-watersheds. More time and effort are also required to set up and to calibrate the SWAT model for different watersheds size and for different time-scale.

Considering the uncertainties in model representation, it is necessary to simulate the processes on sub-daily time-scale, especially in the small watersheds where the processes occur in few hours time-scale.

2.6 References

Abbaspour KC, Johnson CA, van Genuchten MTh. 2004. Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure. *Vadose Zone Journal* **3**:1340-1352.

Abbaspour KC, Vejdani M, Haghighat S. 2007. SWAT-CUP calibration and uncertainty programs for SWAT. In: *Congress on modeling and simulation*, Melbourne, Australia,

2007. Melbourne, Australia, Modeling and Simulation Society of Australia and New Zealand, 2007. p.1603-1609.

Abbaspour KC. 2007. SWAT-CUP: SWAT calibration and uncertainty programs – A user manual. 100p

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G. 2013. Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift* **22**:711-728.

Arnold JG, Fohrer N. 2005. SWAT2000: Current capabilities and research opportunities in applied watershed modeling. *Hydrological Processes* **19**:563-572.

Arnold JG, Kiniry JR, Srinivasan R, Williams JR, Haney EB, Neitsch SL. 2012b. *Soil & Water Assesment Tool: Input/output documentation – version 2012*.

Arnold JG, Moriasi D, Gassman PW, Abbaspour KC, White MJ, Srinivasan R, Santhi C, Harmel RD, van Griensven A, van Liew MW, Kannan N, Jha M. 2012a. SWAT: Model use, calibration, and validation. *Transactions of the ASABE* **55**:1491-1508.

Arnold JG, Muttiah RS, Srinivasan R, Allen PM. 2000. Regional estimation of base flow and groundwater recharge in the Upper Mississippi river basin. *Journal of Hydrology* **227**:21-40.

Arnold JG, Srinivasan R, Muttiah PM, Allen PM. 1999. Continental-scale simulation of the hydrologic balance. *Journal of the American Resources Association* **35**:1037-1052.

Arnold JG, Srinivasan R, Muttiah RS, Williams JR. 1998. Large area hydrologic modeling and assessment. Part I: Model development. *Journal of the American Resources Association* **34**:73-89.

Baumhardt E. 2014. Hidrologia de bacia de cabeceira com eucaliptocultura e campo nativo na região da campanha gaúcha. Doctoral thesis, Universidade Federal de Santa Maria, Santa Maria, Brazil.

Bergamaschi H, Guadagnin MR, Cardoso LS, Silva MIG. 2003. *Clima da Estação Experimental da UFRGS (e região de abrangência)*. Porto Alegre: UFRGS. 77p.

Bergamaschi H, Melo RW, Guadagnin MR, Cardoso LS, Silva MIG, Comiran F, Dalsin F, Tessari ML, Brauner PC. 2013. *Boletins agrometeorológicos da Estação Experimental Agronômica da UFRGS: Série histórica 1970-2012*. Porto Alegre: UFRGS.

Bieger K, Hormann G, Fohrer N. 2015. Detailed spatial analysis of SWAT-simulated surface runoff and sediment yield in a mountainous watershed in China. *Hydrological Sciences Journal* **60**:784-800.

Bonumá NB, Reichert JM, Rodrigues MF, Monteiro JAF, Arnold JG, Srinivasan R. 2015. Modeling surface hydrology, soil erosion, nutrient transport, and future scenarios with the ecohydrological SWAT model in Brazilian watersheds and river basins. In: *Tópicos em Ciência do Solo,* Nascimento CWA, Souza Júnior VS, Freire MBGS, Souza ER (Org.), **IX**:241-290.

Bonumá NB, Rossi CG, Arnold JG, Reichert JM, Minella JPG, Allen PM, Volk M. 2013. Simulating landscape sediment transport capacity by using a modified SWAT Model. *Journal of Environmental Quality* **43**:55-66.

Bonumá NB, Rossi CG, Arnold JG, Reichert JM, Paiva EMCD. 2012. Hydrology evaluation of the Soil and Water Assessment Tool considering measurement uncertainty for a small watershed in Sourthen Brazil. *Applied Engineering in Agriculture* **29**:189-200.

Bonumá NB. 2011. Modelagem do escoamento, da produção de sedimentos e da transferência de fósforo em bacia rural no sul do Brasil. Doctoral thesis, Universidade Federal de Santa Maria, Santa Maria, Brazil.

Borah DK, Yagow G, Saleh A, Barnes PL, Rosenthal W, Krug EC, Hauck LM. 2006. Sedimentation and nutrient modeling for TMDL development and implementation. *Transactions of the ASABE* **49**:967-986.

Costa AM, Curi N, Menezes MD, Araújo EF, Marques JJ. 2009. Levantamento detalhado de solos da microbacia hidrográfica do horto florestal Terra Dura (RS) e considerações sobre escalas de mapeamento. *Ciência e Agrotecnologia* **33**:1272-1279.

Denardin JE. 1990. Erodibilidade de solo estimada por meio de parâmetros físicos e químicos. Doctoral thesis, Escola Superior de Agricultura Luiz de Queiroz da Universidade de São Paulo, Piracicaba, Brazil.

Edwards TK, Glysson GD. 1998. *Field methods for measurement of fluvial sediment*. US Geological Survey Open-File Report 86-531. 118p.

EMBRAPA. 2006. *Sistema Brasileiro de Classificação de Solos*. 2.ed. Brasília: Embrapa. 306p.

Ferreira AG, Gonçalves AC, Dias SS. 2008. Avaliação da Sustentabilidade dos Sistemas Florestais em Função da Erosão. *Silva Lusitana* **16**:55-67.

Fukunaga DC, Cecílio RA, Zanetti SS, Oliveira LT, Caiado MAC. 2015. Application of the SWAT hydrologic model to a tropical watershed at Brazil. *Catena* **125**:206–213.

Green CH, Tomer MD, Di Luzio M, Arnold, JG. 2006. Hydrologic evaluation of the Soil and Water Assessment Tool for a large tile-drained watershed in Iowa. *Transactions of the ASABE* **49**:413-422.

Green CH, van Griensven A. 2008. Autocalibration in hydrologic modeling: Using SWAT2005 in small-scale watersheds. *Environmental Modelling & Software* **23**:422-434.

Guy HP. 1969. *Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations*. Washington, DC, C1 US Government Printing Office, v.5. 58p.

Hargreaves G, Samani ZA. 1985. Reference crop evapotranspiration from temperature. *Transactions of the ASAE* **1**:96-99.

Jha M, Arnold JG, Gassman PW, Giorgi F, Gu R. 2006. Climate change sensitivity assessment on upper Mississippi river basin steam flows using SWAT. *Journal of the American Resources Association* **42**:997-1015.

Lelis TA, Calijuri ML, Santiago AF, Lima DC, Rocha EO. 2012. Análise de sensibilidade e calibração do modelo SWAT aplicado em bacia hidrográfica da região sudeste do Brasil. *Revista Brasileira de Ciência do Solo* **36**: 623-634.

Meaurio M, Zabaleta A, Uriarte JA, Srinivasan R, Antigüedad I. 2015. Evaluation of SWAT models performance to simulate streamflow spatial origin. The case of a small forested watershed. *Journal of Hydrology* **525**:326-334.

Mishra SK, Singh VP. 2003. *Soil Conservation Service Curve Number (SCS-CN) Methodology*. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Moriasi DN, Arnold JG, van Liew MW, Bingner RL, Harmel RD, Veith TL. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE* **50**:885-900.

Neitsch SL, Arnold JG, Kiniry JR, Williams JR. 2005. *Soil and Water Assessment Tool Theoretical Documentation: Version 2005*. Temple, Tex.: Blackland Research Center, Texas Agricultural Experiment Station.

Oliveira AH. 2011. Erosão hídrica e seus componentes na sub-bacia hidrográfica do horto florestal Terra Dura, Eldorado do Sul (RS). Doctoral thesis, Universidade Federal de Lavras, Lavras, Brazil.

Oliveira LT. 2014. Aplicação do modelo SWAT para simular vazões em uma bacia hidrográfica em Aracruz, ES. Master thesis, Universidade Federal do Espírito Santo, Jerônimo Monteiro, Brazil.

PELÁEZ JJZ. 2014. Hidrologia comparativa em bacias hidrográficas com eucalipto e campo. Doctoral thesis, Universidade Federal de Santa Maria, Santa Maria, Brazil.

Porto P, Walling DE, Callegari G. 2009. Investigating the effects of afforestation on soil erosion and sediment mobilization in two small catchments in Southern Italy. *Catena* **79**:181-188.

Post DF, Fimbres A, Matthias AD, Sano EE, Accioly L, Batchily AK, Ferreira LG. 2000. Predicting soil albedo from soil color and spectral reflectance data. *Soil Science Society of American Journal* **64**:1027-1034.

Qiu L, Zheng F, Yin R. 2012. SWAT-based runoff and sediment simulation in a small watershed, the loessial hilly-gullied region of China: capabilities and challenges. *International Journal of Sediment Research* **27**:226-234.

Ramgrab GE, Wildner W, Lopes RC, Favilla CAC, Silva MAS, Sachs LLB, Silva VA, Batista IH. 2004. Folha SH.22 – Porto Alegre. In: *Carta Geológica do Brasil ao Milionésimo, Sistema de Informações Geográficas.* Programa Geologia do Brasil. Brasília, CPRM. Schobbenhaus C, Gonçalves JH, Santos JOS, Abram MB, Leão Neto R, Matos GMM, Vidotti RM, Ramos MAB, Jesus JDA. (Eds.). Available in: <http://www.cprm.gov.br/publique/cgi/cgilua.exe/sys/start.htm?infoid=298&sid=26>.

Ranzini M, Lima WP. 2002. Comportamento hidrológico, balanço de nutrientes e perdas de solo em duas microbacias reflorestadas com Eucalyptus, no Vale do Paraíba, SP. *Scientia Forestalis* **61**:144-159.

Rodrigues MF, Reichert JM, Minella JPG, Dalbianco L, Ludwig RL, Ramon R, Rodrigues LA, Borges Júnior N. 2014. Hydrosedimentology of nested subtropical watersheds with native and eucalyptus forests. *Journal of Soils and Sediments* **14**:1311-1324.

Rodrigues MF. 2011. Monitoramento e modelagem dos processos hidrossedimentológicos em bacias hidrográficas florestais no sul do Brasil. Master thesis, Universidade Federal de Santa Maria, Santa Maria, Brazil.

Santhi C, Arnold JG, Williams JR, Dugas WA, Srinivasan R, Hauck LM. 2001. Validation of the SWAT model on a large river basin with point and nonpoint sources. *Journal of The American Water Resources Association* **37**:1169-1188.

Schmalz B, Fohrer N. 2009. Comparing model sensitivities of different landscapes using the ecohydrological SWAT model. *Advances in Geoscience* **21**:91-98.

Schoenholtz SH, Miegroet H, Burger JA. 2000. A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities. *Forest Ecology & Management* **138**:335-356.

Setegn SG, Srinivasan R, Melesse AM, Dargahi B. 2010. SWAT model application and prediction uncertainty analysis in the Lake Tana Basin, Ethiopia. *Hydrological Processes* **24**:357-367.

Sheridan GJ, Noske PJ, Whipp RK, Wijesinghe N. 2006. The effect of truck traffic and road water content on sediment delivery from unpaved forest roads. *Hydrological Processes* **20**:1683-1699.

Silva AM. 2004. Rainfall erosivity map for Brazil. *Catena* **57**:251-259.

Singh VP, Woolhiser DA. 2002. Mathematical modeling of watershed hydrology. *Journal of Hydrologic Engineering* **7**:270-292.

Strahler AN. 1957. Quantitative analysis of watershed geomorphology. *Transaction of American Geophysical Union* **38**:913-920.

Strauch M, Volk M. 2013. SWAT plant growth modification for improved modeling of perennial vegetation in the tropics. *Ecological Modelling* **269**:98-112.

USDA - United States Department of Agriculture. 1999. *Soil Survey Staff. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys*. 2nd ed. U.S. Department of Agriculture/Natural Resources Conservations Service, Washington, Agriculture Handbook. 871pp.

Uzeika T, Merten GH, Minella JPG, Moro M. 2012. Use of the SWAT model for hydro-sedimentologic simulation in a small rural watershed. *Revista Brasileira de Ciência do Solo* **36**:557-565.

van Griensven A, Meixner T, Grunwald S, Bishop T, Di Luzio M, Srinivasan R. 2006. A global sensitivity analysis tool for the parameters of multi-variable catchment models. *Journal of Hydrology* **324**:10-23.

Vital ART, Lima WP, Camargo FRA. 1999. Efeitos do corte raso de plantação de Eucalyptus sobre o balanço hídrico, a qualidade da água e as perdas de solo e de nutrientes em uma microbacia no Vale do Paraíba, SP. *Scientia Forestalis* **55**:5-16.

Wu Y, Chen J. 2009. Simulation of nitrogen and phosphorus loads in the Dongjiang River basin in South China using SWAT. *Frontiers of Earth Science in China* **3**:273-278.

3 ARTICLE II: PAIRED WATERSHEDS WITH EUCALYPTUS AND NATURAL GRASSLAND IN BRAZILIAN PAMPA BIOME: ECOHYDROLOGICAL MODELING WITH SWAT

Abstract

Grasslands in Pampa Biome have largely been transformed into forests dominated by commercial eucalyptus stands, with great uncertainty of associated changes in hydrological cycle, water budget, and erosive processes. While the Soil and Water Assessment Tool (SWAT) model has been applied in a few paired watersheds containing grassland and forest to evaluate and to predict hydrological processes, understanding of erosion processes has not been the main goal. For this study, SWAT was used to evaluate hydrological and erosion processes for two paired watersheds in Pampa Biome, Southern Brazil; one with natural grassland (1.10 km^2) and the other with eucalyptus (0.83 km^2). Measured discharge at the watersheds' outlets was used to evaluate model streamflow sensitivity to selected parameters, as well as for calibration from 2009 to 2013. Time series plots and standard statistical measures were used to verify model predictions. Predicted monthly streamflow was "good" during calibration for the grassland watershed (NSE = 0.71, RSR = 0.54, PBIAS = 0.7% and R^2 = 0.71) and the eucalyptus watershed (NSE = 0.71, RSR = 0.54, PBIAS = 4.9% and R^2 = 0.78). Predicted monthly sediment yield was "satisfactory" (NSE = 0.64, RSR = 0.60, PBIAS = 35.2% and R^2 = 0.74) for the grassland watershed, and "very good" (NSE = 0.85, RSR = 0.38 and R^2 = 0.92) and "satisfactory" (PBIAS = 31.9%) for the eucalyptus watershed. Simulations on daily time-scale were "satisfactory" to predict streamflow in both grassland and eucalyptus watersheds. Simulations were better for daily than monthly -scale for streamflow (NSE = 0.81, RSR = 0.43, PBIAS = 13.6 and R^2 = 0.82) and sediment yield (NSE = 0.78 and R^2 = 0.82) for the grassland watershed, and for streamflow (NSE = 0.85, RSR = 0.38, PBIAS = 16.6 and R^2 = 0.86) and sediment yield (NSE = 0.86 and R^2 = 0.86) for the eucalyptus watershed. These results suggest that the SWAT model is a promising tool to simulate hydrology and erosion processes in paired watersheds in order to evaluate the effect of drastic changes in land use. However, more field work is required to understand hydrological and sedimentological variations in small watersheds under natural grassland and forest in the Pampa Biome.

Keywords: forest hydrology; grassland hydrology; erosion and sedimentation; Soil & Water Assessment Tool; commercial forests.

3.1. Introduction

Eucalyptus has become the main species used in commercial forest plantations for industrial purposes in Brazil, where in 2012 the area of eucalypt plantations totaled 5.102 million ha (ABRAF, 2013). In Rio Grande do Sul State, plantations totaled 284,701 ha, covering areas previously used for agriculture and cattle breeding. A significant proportion of this area is located in the southern grassland or Pampa Biome, also called Campos Biome due to differences in vegetation and climate of the Argentine and Uruguayan Pampas Biome.

Ecological concerns for biodiversity and water consumption by forested landscapes on land in the Pampa Biome are expressed by society, but there are almost no scientific studies available. There is some information on the role of forests in global climate change (Streck and Scholz, 2006); in silvicultural, social, and ecological aspects (Evans and Turnbull, 2004); and in hydrological aspects (Molchanov, 1963). However, more studies are needed to better understand the impact of forest on the hydrological cycle (Andréassian, 2004; Baumhardt, 2010, 2014; Oki Kanae, 2006), and on the impact of forest on erosive processes, and ecological effects in specific biomes.

Forest plantations may reduce surface flow and soil water availability in small watersheds (Van Dijk et al., 2007), and increase groundwater recharge by improving infiltration (Van Dijk and Keenan, 2007). Hydrological changes affect downstream conditions, soil yield potential, and watershed health. These changes also generate conflicts over water use and are key issues in sustainable land management (Calder, 2007; Lima, 2005; Vanclay, 2009).

Few studies, however, have provided information on the effects of forests on erosion and sediment yield at the watershed scale in tropical and subtropical regions (Ranzini and Lima, 2002; Vital et al., 1999), and the effectiveness of commercial forests in erosion control is uncertain, either due to species cultivated or the soil protection provided by canopy coverage and litter (Porto et al., 2009). Although forest canopy provides soil surface protection (even for eucalyptus with its less-dense canopy) (Porto et al., 2009), management operations, harvesting, and construction and maintenance of roads in eucalyptus plantations increase susceptibility to water erosion (Ferreira et al., 2008; Oliveira, 2011; Porto et al., 2009; Schoenholtz et al., 2000; Sheridan et al., 2006).

Models are important tools for providing knowledge of hydrosedimentological processes to decision-makers for planning the rational use of natural resources. The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Arnold and Fohrer, 2005) has been widely used successfully to evaluate the effects of land use and soil management on hydrology, sediment yield, and water quality (Borah et al., 2006). In Brazil, SWAT has good potential to be used as a support tool for planning appropriate land uses to improve water quality in rural areas with annual crops (Bonumá et al., 2012, 2013, 2015; Bressiani et al., 2015; Uzeika et al., 2012) and with eucalyptus forest (Oliveira, 2014), .

Therefore, SWAT must be critically examined for its appropriate use in subtropical small watersheds since the model was originally designed for temperate regions (Strauch and Volk, 2013) and for large watersheds (Arnold et al., 1998) where the time of concentration is greater than one day. When applied in regions with scarce or incomplete data, and where climate, soils, plants, and agricultural management practices differ from temperate environments, parameter calibration is necessary (Bieger et al., 2015). One major concern is the simulation of perennial tropical vegetation due to absence of dormancy and/or long cycle for maturity, as is the case for eucalyptus species. Paired watersheds may eliminate the potentially confounding edaphic and topographic influences from changes in hydrological processes related to eucalyptus stands (Quiao et al., 2015).

We monitored and modeled two paired watersheds in order to characterize the hydrological and sedimentological processes for different land use conditions and water availability to support decision making in land use and soil and water resources management. We aimed to evaluate the effects of eucalyptus cultivation on hydrosedimentological processes in paired watersheds, and the efficiency and limitations of SWAT to simulate at different time-scales (daily and monthly) the effects of vegetation on runoff, streamflow, and sediment yield dynamics in paired watersheds.

3.2. Materials and methods

3.2.1. Paired watershed properties

The study was conducted in two paired watersheds, one with eucalyptus (FW) and the other with natural grassland (GW) for cattle grazing (Fig. 1). The watersheds are located in São Gabriel municipality, Rio Grande do Sul State, Brazil. Both watersheds drain into the Vacacaí and Vacacaí-Mirim river basins, which in turn drain into the Guaíba river basin, part of the National Hydrographic Region South Atlantic, and finally into the Atlantic Ocean.

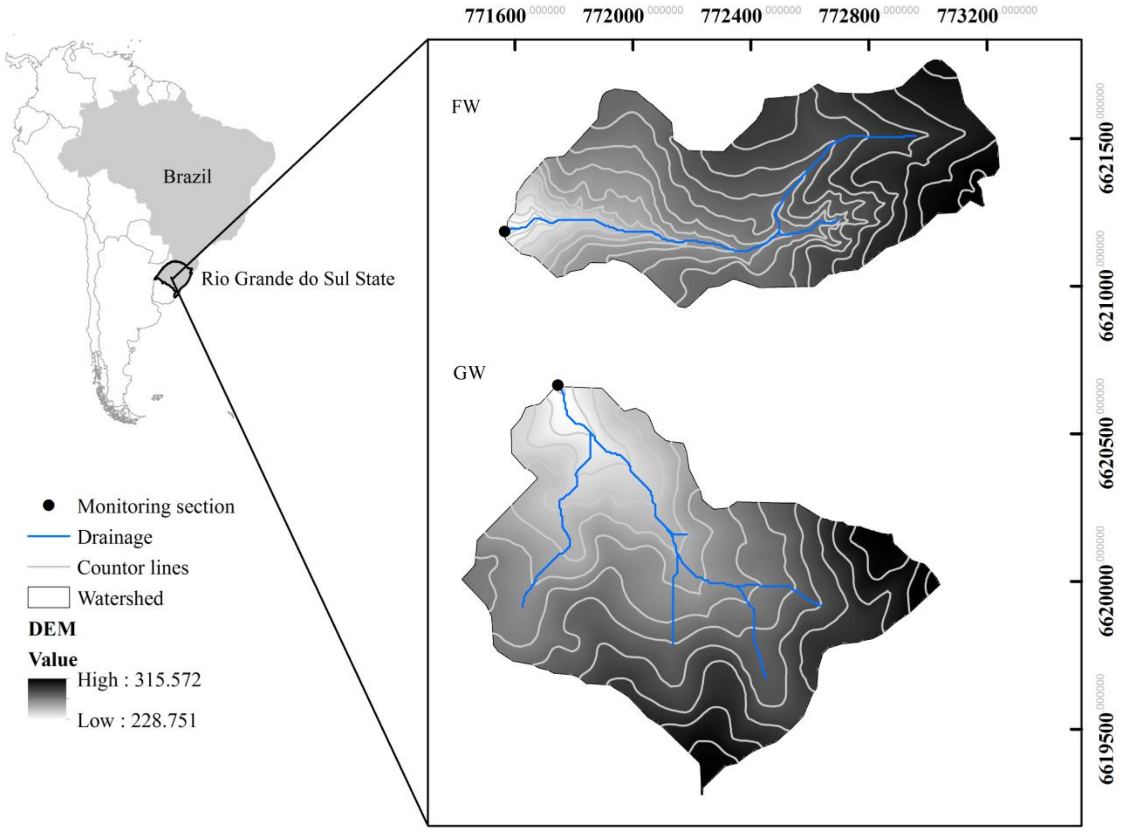

Fig. 1. Location of the grassland watershed (GW) and eucalyptus watershed (FW), in Brazilian Pampa Biome, São Gabriel-RS, Southern Brazil.

Climate is Cfa, humid subtropical, with no drought, according to Köppen classification (Álvares et al., 2013), with an average annual temperature of 18.6 °C, a warmest month average temperature of 31 ºC and a coolest month average temperature of 5 ºC (Moreno, 1961). Monthly precipitation averages are all above 60 mm, and average annual rainfall is 1356 mm (Moreno, 1961). Although rainfall is well distributed throughout the year, drought events are recurrent and frequent in the region (Atlas Sócio-econômico do Rio Grande do Sul, 2008).

Soils in both watersheds are derived from the decomposition of metamorphic rocks and granite-gneiss (amphibolite metamorphism; orthogneiss lithologies, metadiorite, and metaperidotite) (Ramgrab et al., 2004).

The watershed occupied with eucalyptus forest (*Eucalyptus saligna*) (FW) is situated between the geographical coordinates 30º30'18" and 30º30'47" latitude South and 54º09'09" and 54º10'17" West longitude (Fig. 1). FW has a drainage area of 0.83 km^2, perimeter of 4.17 km, a 1.51 coefficient of compactness, and average time of concentration of 15.5 min calculated based on watershed morphometry. The river hierarchy is of second order, in which channels originate from the junction of two channels of first order (Strahler, 1957).

The FW landscape is characterized by elevations between 230 and 315 m asl, with an average altitude of 271.84 m and mean slope of 7.7%. Soils are classified as *Argissolo Vermelho*, *Argissolo Vermelho-Amarelo*, *Cambissolo Háplico* and *Neossolo Regolítico* according to the Brazilian Soil Classification System (EMBRAPA, 2006), and Ultisols, Ultisols, Inceptisols, and Entisols, respectively, according to the Soil Taxonomy (USDA, 1999) (Fig. 2). Land use is mainly *Eucalyptus saligna* (61.60% of total area of FW), but also contains grassland with brush-weeds (22.07%), riparian vegetation (7.95%), unpaved roads (5.77%), and outcrops (2.61%) (Fig. 2).

Eucalyptus stands were planted in 2006 (7-years old during the study period) with 3.0 x 3.3-m spacing. The trees had an average diameter at breast height (DBH) of 17 cm and average and height of 25 m. Grassland with bushy-weeds consisted of grasses and shrubs, in which *Aloysia gratissima* (Verbenaceae) and *Heterothalamus alienus* (Asteraceae) were the most abundant species. The riparian forest was formed by arboreal stratum of the native species, with individuals 6-8 m tall, consisting of *Sebastiania commersoniana*, *Rollinia salicifolia*, *Styrax leprosus*, *Eugenia uniflora*, *Luehea divaricata*, *Casearia decandra*, *Diospyros inconstans*, *Myrcianthes pungens* and *Ocotea* ssp.

The watershed under natural grassland (GW) is located within the geographic coordinates 30º30'54 " and 30º31'35 " South latitude and 54º09'17 " and 54º10'14 "West longitude (Fig. 1). The GW represents a regional biome where the rich biodiversity is in faster transformation to cultivate forest and agricultural monocultures. GW has a drainage area of 1.10 km^2 and a perimeter of 4.32 km, with a 1.22 coefficient of compactness, and average time of concentration of 18.8 min. The GW fluvial hierarchy is of second order (Strahler, 1957).

The GW landscape is characterized by elevations between 255 and 310 m asl, with an average altitude of 273.36 m and mean slope of 3.08%. Soils are classified as *Argissolo Vermelho*, *Argissolo Vermelho-Amarelo* and *Cambissolo Háplico* according to the Brazilian Soil Classification System (EMBRAPA, 2006), and as Ultisols, Ultisols and Inceptisols, respectively, according to Soil Taxonomy (USDA, 1999) (Fig. 2). Land uses were native grassland (61.68% of the total area of the GW), pasture with oat (*Avena strigosa*) (31.05%), eucalypt and isolated trees (3.32%), native forest and riparian forest (2.13%), water reservoir (1.73%), and buildings (0.09%) (Fig. 2).

The GW upper vegetation stratum was mainly composed of *Saccharum angustifolium*, *Aristida laevis*, *Baccharis riograndensis*, *Andropogon lateralis*, and E*ryngium pandanifolium*, whereas the lower statum was *Paspalum* ssp., *Axonopus affinis*, and *Fimbristylis autumnalis*. Pasture is annually overseeded with oats. Small isolated Eucalyptus stands had individuals older than 20 years, higher than 25 m, and DBH between 20 and 120 cm. *Ficus luschnathiana*, *Acca sellowiana*, and *Sebastiania commersoniana* occur in arboreal clumps or as isolated individuals. The riparian vegetation was formed by arboreal stratum of the native species *Sebastiania commersoniana*, *Myrcia bombycina*, *Sapium longifolium*, *Mimosa pilulifera*, *Luehea divaricata*, *Calliandra tweediei*, *Maytenus muelleri*, and *Calliandra brevipes*.

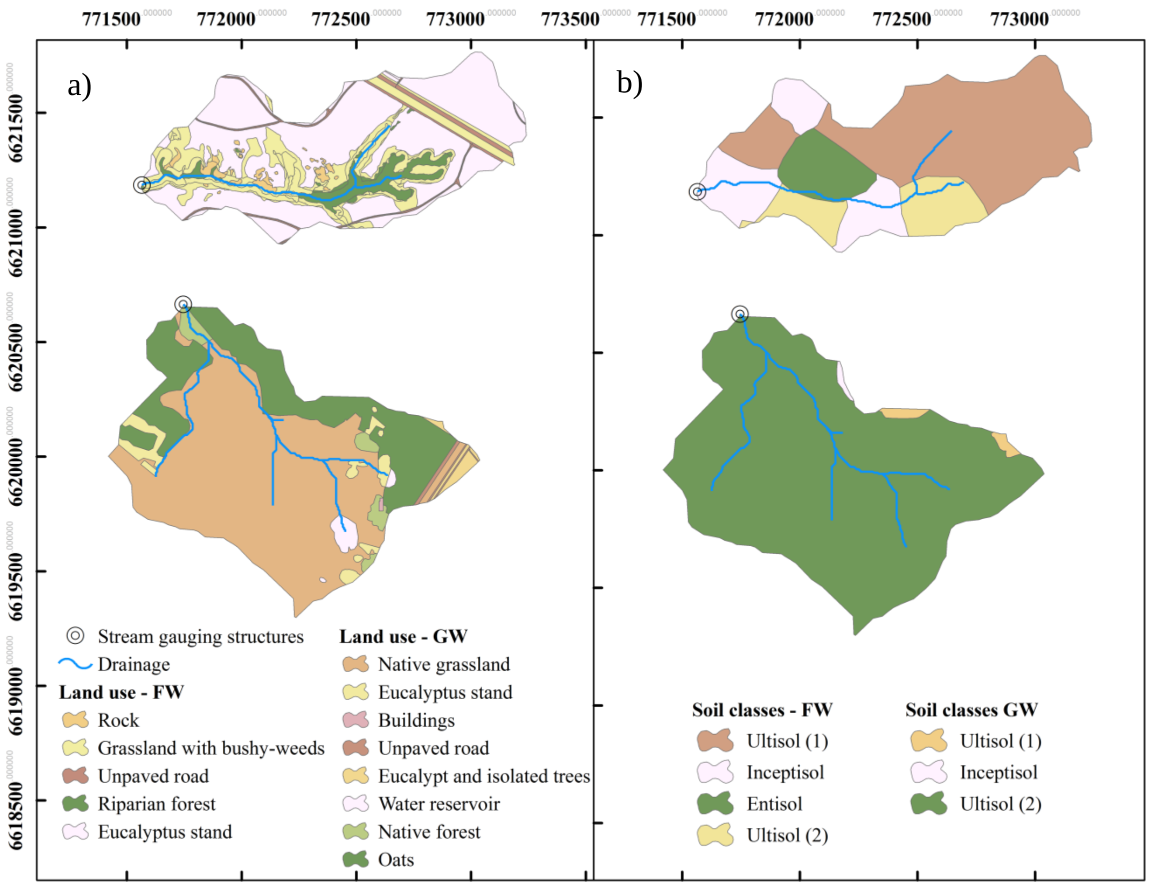

Figure 2. Land use (a) and soil classes (b) of the studied watersheds, in São Gabriel-RS, southern Brazil.

*Ultisol (1): *Argissolo Vermelho*; Ultisol (2): *Argissolo Vermelho-Amarelo*; Inceptisol: *Cambissolo Háplico*; Planosol: *Planossolo Háplico*.

3.2.2. Hydrosedimentometric monitoring

Hydrosedimentometric monitoring was conducted from 08/01/2012 to 09/30/2013 in automated monitoring sections, instrumented with sensors for water level (limnigraphs), turbidity (turbiditymeters) and rainfall (rain gauges). Sensors were installed near the triangular weirs installed at the watershed outlet, whereas dataloggers were programmed to record data at fixed 10-minute intervals.

Suspended sediment was sampled manually during rainfall-runoff-sediment events with a USDH-48 sampler (Edwards and Glysson, 1998) to obtain time-series data of sediment concentration, which was determined by the evaporation method (Guy, 1969). Due to the need for continuous data acquisition, turbidity measurements were used for estimating suspended sediment concentration. This device provides data for estimating the concentration of suspended sediments based on the relationship between the suspended sediment concentration, obtained either during flood events or from sediment concentrations prepared in laboratory, with fine sediments collected from the drainage network.

Bed load was monitored with a BLH-84 sampler. Direct measurements of bed discharge of sediments were conducted across the whole section width at five equidistant points, collecting 40 subsamples to compose a sample. After collection, samples were taken to the laboratory where sediment load was quantified by drying and weighing. Besides the direct method using samplers, a bathymetric survey was also conducted at the beginning and at the end of the monitoring period to quantify sediment volume retained by the weir. The triangular weir has the capability of accumulate flood waves and reduce flood ability to transport coarser particles, which are deposited upstream of the weir.

Total suspended sediment yield was determined from the integrated solid discharge obtained during automatic monitoring period, whilst the total bed discharge of sediments was determined dividing the total sediment accumulated in the weir in one year by the number of the days in the year. Total sediment yield was determined by the sum of the suspended and bed sediment yield.

During the study period (08/01/2012 to 09/30/2013) the rainfall was 1822.37 mm, the sediment yield was 7.13 Mg km^{-2}, and the average streamflow was 0.00403 m^{3} s^{-1} for the eucalyptus watershed; whilst for the grassland watershed, the rainfall was 1840.99 mm, the sediment yield was 61.13 Mg km^{-2}, and the average streamflow was 0.01446 m^{3} s^{-1}.

3.2.3. SWAT model

The SWAT model is an ecohydrological model for watershed scale, usually applied in continuous-time simulations which can be discretized on monthly, daily, and sub-daily scales (Arnold et al., 1998). Thus, input data to feed the model must be adjusted to spatial and temporal dynamics of processes occurring in the target watershed. Required input data are cartographic databases as data layers and tabular data, which are inserted through an appropriate interface. Required layers are digital elevation model (DEM), soil classes, land use/management, and watershed limits (Bonumá et al., 2015; Uzeika et al., 2012).

An interface developed between SWAT and ArcSWAT, in addition to facilitating data input in the model, automatically subdivides the watershed into sub-sections based on DEM and drainage network and then lists the input data for each sub-watershed. Each cell in a DEM is assumed to flow to one of eight neighboring cells according to steepest-slope direction. SWAT simulates a watershed by dividing it into multiple sub-watersheds which are further divided into hydrologic response units (HRUs) as the product of overlaying soil, land use, and slope classes.

Topographic data were obtained by digitizing topographic contour lines with 5-m intervals. The digitized contour vectors were used to create a Triangular Irregular Network (TIN) for generating a Digital Elevation Model (DEM) with 5-m spatial pixel resolution. The DEM, watershed outlet point, and digitized drainage network were used to delineate and for partitioning the watershed into sub-watersheds and reaches. The slope map was divided in three slope classes: 0-2%, 2-10%, and >10%, as recommended for non-hilly topography. Information extracted and calculated from the DEM includes overland slope, slope length, and elevation corrections for precipitation and evapotranspiration.

Land use data over the period of the study was determined by field surveys, assisted by a geographic positioning system with GIS software, and checked in Google Earth®. Operation dates vary per year depending on cumulative days exceeding the minimum (base) temperature for plant growth (Bonumá, 2011), and this calculation is particularly important for southern hemisphere conditions. Potential heat units for crops were calculated and values were added to the management input file (.mgt file).

The digital soil map (1:10,000) identifies four soil classes: Ultisols (2), Inceptisols (1), and Entisols (1). Key soil physical properties such as soil granulometry, bulk density, porosity, and available water were analyzed for each soil and horizon, and the information was added to the SWAT user soils databases (.usersoil file).

Soil albedo was determined by the equation (Soil albedo (0.3-2.8 Mm) = 0.69 (color value) - 0.114; r^2 = 0.93) proposed by Post et al. (2000). Soil erodibility was determined with the equation proposed by Denardin (1990) for Brazilian soils (K = 0.006084 P + 8.34286 (10^{-4}) OM – 1.1616 (10^{-4}) Al – 3.776 (10^{-5}) CS), where: K = erodibility (t ha h ha^{-1} MJ^{-1} mm^{-1}); P = permeability of soil profile (1 - fast; 2 – moderate/fast; 3 - moderate; 4 - slow/moderate; 5 - slow; 6 – very slow); OM = organic matter (g kg^{-1}); Al = Al_2O_3 extracted by sulfuric acid (g kg^{-1}); and CS = coarse sand (0.5-2.0 mm) (g kg^{-1}). Additional soil parameters were taken from a previous study developed in the watershed (Morales, 2013).

The number of HRUs is limited by the precision of input digital maps (Bonumá, 2011). A realistic combination of land uses, soil classes and slope classes, with a zero (0) percent threshold area resulted in 72 HRUs and 7 sub-watersheds for the grassland watershed and 84 HRUs and 3 sub-watersheds for the eucalyptus watershed (Fig. 3).

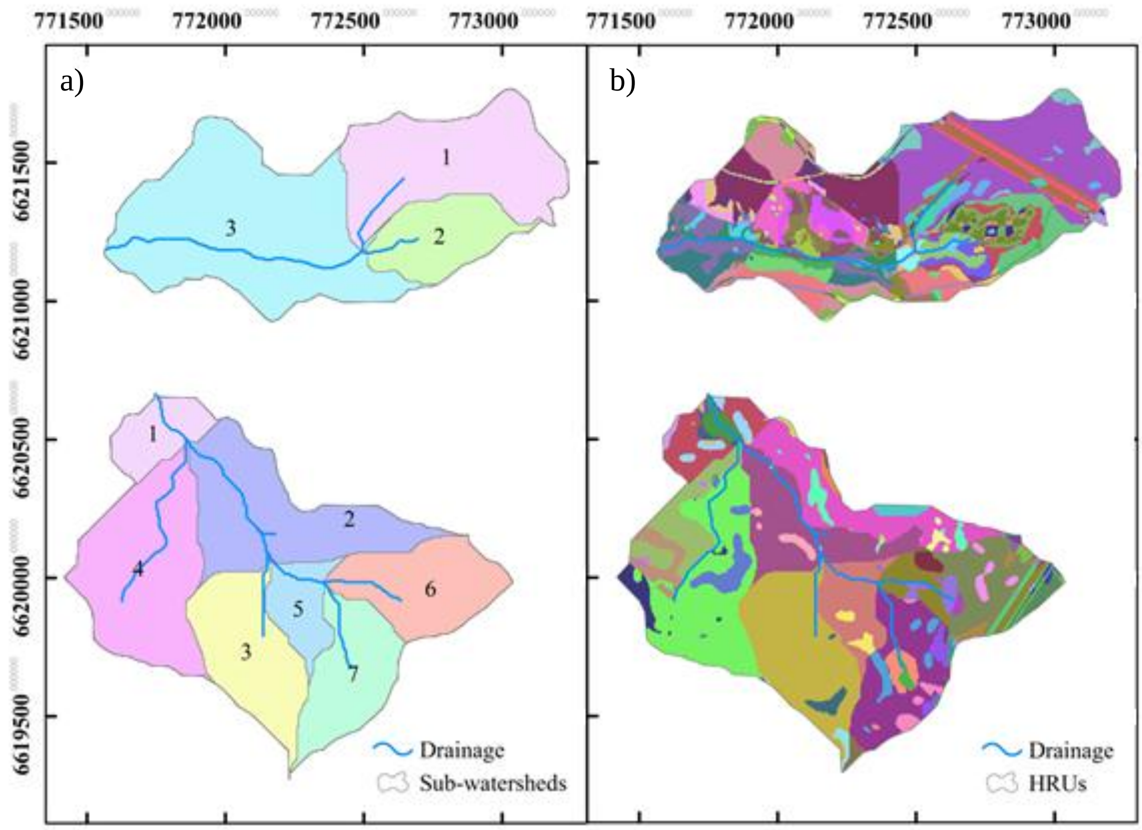

Fig. 3. Sub-watersheds (a) and HRUs (b) delineated by the SWAT model, São Gabriel-RS, Southern Brazil.

Rainfall and climate data were collected and used from 01/01/2009 to 12/31/2014. Rainfall data were obtained from an automatic meteorological station and from an automatic rain gauge installed within the watershed. Climate data were obtained from an automatic meteorological station installed within the watershed, and gaps in climate data were completed with information from the National Institute of Meteorology (Instituto Nacional de Meteorologia-INMET) located in the municipality of São Gabriel-RS. Climate data from INMET Station were also used for weather generator input data. Daily maximum and minimum air temperature, solar radiation, wind speed, and relative humidity values were also obtained from the automatic meteorological stations. The Hargreaves-Samani method (Hargreaves and Samani, 1985) was then applied to estimate evapotranspiration and to establish the water balance of each HRU by using the meteorological data. Simulations from 01/01/2009 to 12/31/2014 were performed with SWAT2012, for monthly and daily time-scale, for both GW and FW, whilst the sub-daily time-scale was not used due this option is not available in SWAT2012 version. Rainfall and climate data from 01/01/2009 to 12/31/2012 served as a model parameter value initialization period ("model warm-up"). Streamflow and sediment yield data obtained in the outlet gauge from 01/01/2012 to 12/31/2014 were used for streamflow and sediment yield simulation on monthly and daily scales.

3.2.4. Model calibration

SWAT calibration was performed using the SWAT-CUP software (Abbaspour et al., 2007; Arnold et al., 2012b). All SWAT parameters can be included in the calibration process (Arnold et al., 2012b). Sensitivity analysis and calibration procedure were carried out using 24 parameters of the SWAT model that have been suggested as being the most sensitive for streamflow (Abbaspour et al., 2007; van Griensven et al., 2006) and sediment yield (Abbaspour et al., 2007) simulations.

The optimization technique used was Sequential Uncertainty Fitting algorithm (SUFI-2) (Abbaspour et al., 2007). The SUFI-2 combines optimization with uncertainty analysis and can handle a large number of parameters (Abbaspour et al., 2004). The SUFI-2 procedure perform inverse modeling using a sequence of steps in which the initial (large) uncertainties in the model parameters are progressively reduced until reaching a certain calibration requirement that is based on the prediction uncertainty (Abbaspour et al., 2004). The degree to which all uncertainties are accounted for is quantified by a measure referred to as the P-factor, which is the percentage of measured data bracketed by the 95% prediction uncertainty (Abbaspour, 2007). Firstly, an objective function was defined: Nash–Sutcliffe efficiency coefficient greater than 0.5. Thereafter, physically-meaningful absolute minimum and maximum ranges for the parameters being optimized was established.

SWAT performance was evaluated using graphical comparison and statistical analysis to determine quality and reliability of predictions when compared to measured monthly and daily streamflow and sediment yield values. We chose as standards for “acceptable” simulations $R^2 > 0.6$ (Bonumá et al., 2012, 2013; Santhi et al., 2001), NSE > 0.50, and RSR ≤ 0.70 for streamflow and sediment, PBIAS ± 25% for streamflow and PBIAS ± 55% for sediment (Moriasi et al., 2007) for a monthly time step.

When watershed models are evaluated on daily time step, the ratings can be less strict than for longer time steps (Moriasi et al., 2007). To assess how well the model performed for a daily time step, we used Green and van Griensven’s (2008) and Wu and Chen’s (2009) standards of NSE > 0.4 and $R^2 > 0.5$ as being “satisfactory” results.

3.3. Results

3.3.1. Sensitivity analysis

Parameter sensitivity on monthly time-scale was different between GW and FW for most parameters (Fig. 4). For streamflow and sediment yield, in both GW and FW, maximum canopy storage (CANMX) was the most sensitive parameter. Subsequently to CANMAX, in descending order, sensitivity analysis for GW showed the most sensitive parameters for the two variables were moist soil albedo (SOL_ALB); threshold depth for return flow of water in the shallow aquifer (GWQMIN); surface runoff lag time (SURLAG); effective hydraulic conductivity in the main channel alluvium (CH_K2); maximum potential leaf area index for land cover/plants (BLAI); available water capacity of soil (SOL_AWC); Manning's roughness coefficient value for the main channel (CH_N2); depth to bottom of soil layer n (SOL_ZMX); initial SCS runoff curve number for moisture condition II (CN2); soil hydraulic conductivity (SOL_K); groundwater “revap” coefficient (GW_REVAP); soil evaporation compensation factor (ESCO); plant uptake compensation factor (EPCO); deep aquifer percolation fraction (RCHRG_DP); baseflow recession constant (ALPHA_BF); and threshold depth for “revap” of water in the shallow aquifer (REVAPMN); groundwater delay (GW_DELAY); and biological mixing efficiency (BIOMIX) (Fig. 4a). For FW, sensitivity analysis showed that the most sensitive parameters for all variables were CANMX, EPCO, GW_DELAY, ESCO, BIOMIX, RCHRG_DP, CH_N2, SOL_ALB, GW_REVAP, CH_K2, SURLAG, BLAI, SOL_AWC, CN2, SOL_K, REVAPMN, GWQMIN, SOL_Z, and ALPHA_BF, in descending order (Fig. 4b).

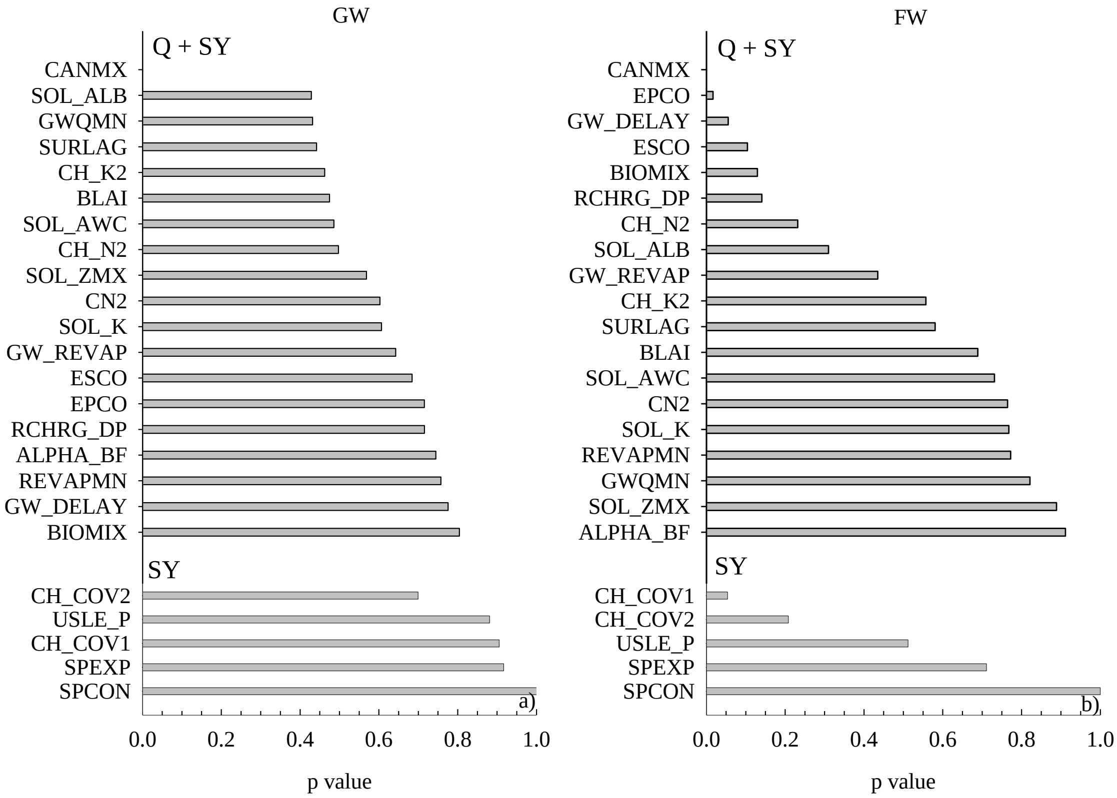

Fig. 4. Sensitive parameters on monthly time-scale for streamflow and sediment yield (Q + SY) and for sediment only (SY) for grassland watershed (GW) (a) and eucalyptus watershed (FW) (b).

For sediment yield in the GW, sensitivity analysis showed that the most sensitive parameters, in descending order, were: channel cover factor (CH_COV2); USLE equation support practice factor (USLE_P); channel cover factors (CH_COV1); exponent parameter for calculating sediment re-entrained in channel sediment routing (SPEXP); and linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing (SPCON) (Fig. 4a). Sensitivity analysis for FW showed that the most sensitive parameters were CH_COV1 and CH_COV2, USLE_P, SPEXP, and SPCON, in descending order (Fig. 4b).

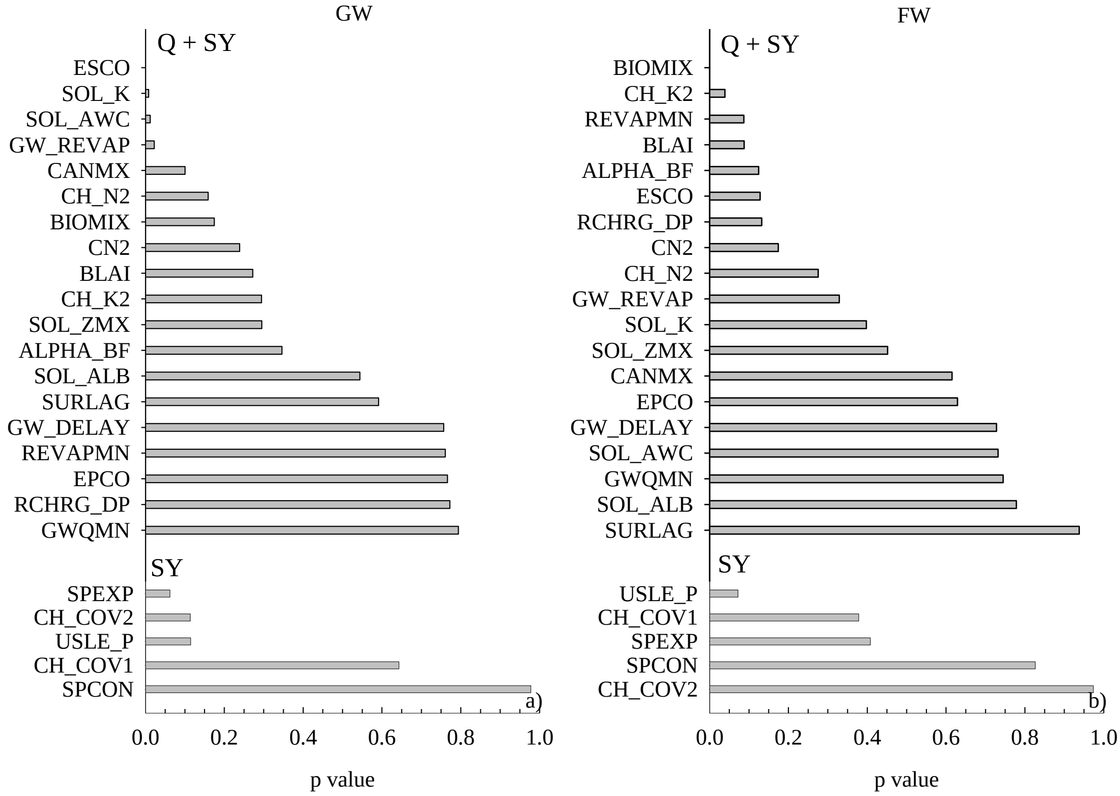

Fig. 5. Sensitive parameters on daily time-scale for streamflow and sediment yield (Q + SY), and for sediment only (SY) for grassland watershed (GW) (a) and eucalyptus watershed (FW) (b).

Parameter sensitivity was different between GW and FW for most parameters on daily time-scale evaluation (Fig. 5). For streamflow and sediment yield, ESCO, SOL_K, SOL_WAC, GW_REVAP, CANMX, CH_N2, and BIOMIX were the most sensitive parameters in the GW (Fig. 5a), while for FW the most sensitive parameters were BIOMIX, CH_K2, REVAPMN, BLAI, ALPHA_BF, ESCO, RCHRG_DP, and CH_N2, in descending order (Fig. 5b); the other parameters had low sensitivity.

Further, for sediment in the GW, sensitivity analysis showed that the most sensitive parameters, in descending order, were: SPCON, CH_COV2, and USLE_P (Fig. 5a). Sensitivity analysis for the FW showed that the most sensitive parameters were USLE_P, CH_COV1, and SPEXP, in descending order (Fig. 5b).

3.3.2. Monthly streamflow and sediment yield

Monthly observed and simulated streamflow matched well during the calibration period for both grassland and eucalyptus watersheds (Fig. 6). Model performance to represent streamflow was “good” for the calibration period for both GW and FW, as supported by

Moriasi et al. (2007); NSE was 0.71 (0.65 < NSE <= 0.75) and the RSR value was 0.54 (0.50 <= RSR <= 0.60), was and PBIAS indicated "very good" performance with values of 0.7% for GW and 4.9% for FW (modular value < 10%). Monthly calibration R^2 values were 0.71 and 0.78 (> 0.6) for the grassland and eucalyptus watersheds, respectively (Fig. 7), results that were considered to be "acceptable".

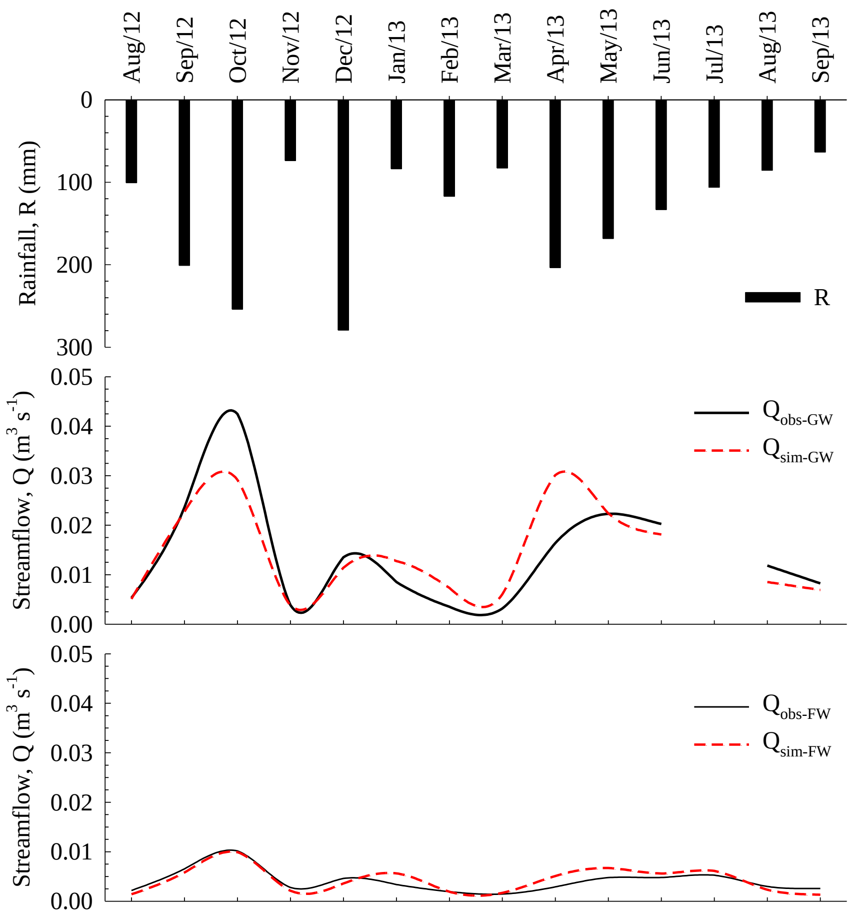

Fig. 6. Monthly rainfall (R) and observed and simulated streamflow for grassland watershed (Q_{obs-GW} and Q_{sim-GW}) and for eucalyptus watershed (Q_{obs-FW} and Q_{sim-FW}) outlets.

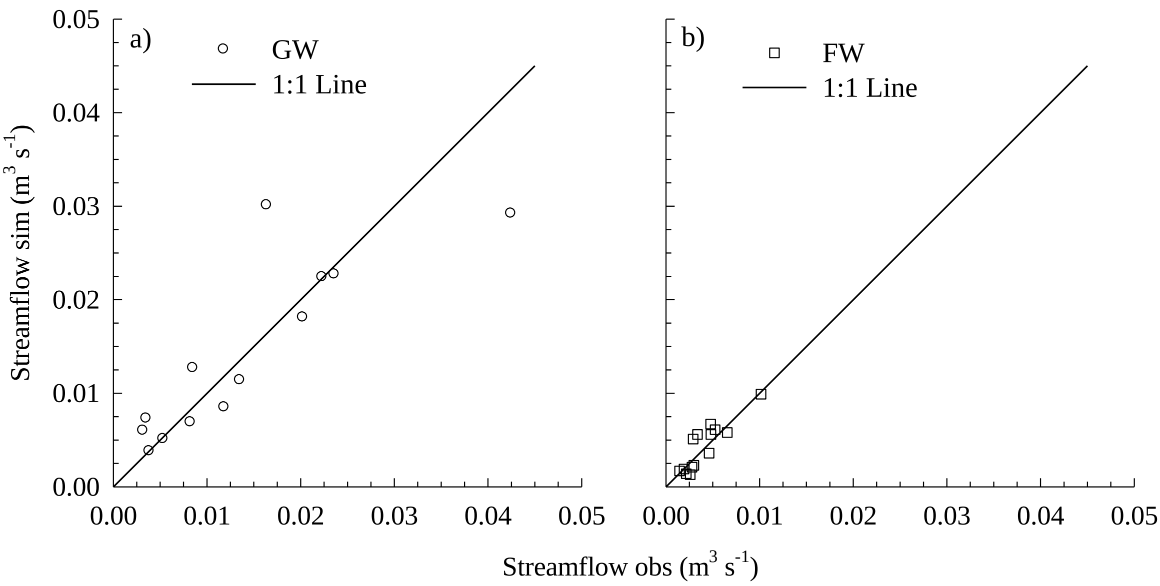

Fig. 7. Monthly dispersion diagram of observed and simulated streamflow for the grassland watershed (GW) (a) and the eucalyptus watershed (FW) (b). *Sim: simulated; Obs: observed.

Monthly observed and simulated sediment yield matched well during the calibration period for both the grassland and the eucalyptus watersheds (Fig. 8), with sediment yields that were underpredicted in some months and overpredicted in others. Monthly calibration R^2 values were 0.74 and 0.92 for the grassland watershed and eucalyptus watershed, respectively (Fig. 9), which were considered “acceptable” (> 0.6).

Model performance for sediment yield for the grassland watershed during the calibration period was “satisfactory”, as supported by an NSE value of 0.64 (0.50 < NSE <= 0.65), an RSR of 0.60 (0.50 <= RSR <= 0.60), and a PBIAS of 35.2% (modular value 30 ≤ PBIAS ≤ 50%). For the eucalyptus watershed, statistical parameters were “very good”, as supported by an NSE of 0.85 (> 0.75) and an RSR of 0.38 (< 0.50), but was indicated to be “satisfactory” by the PBIAS value of 31.9% (modular value 30 ≤ PBIAS ≤ 50%).

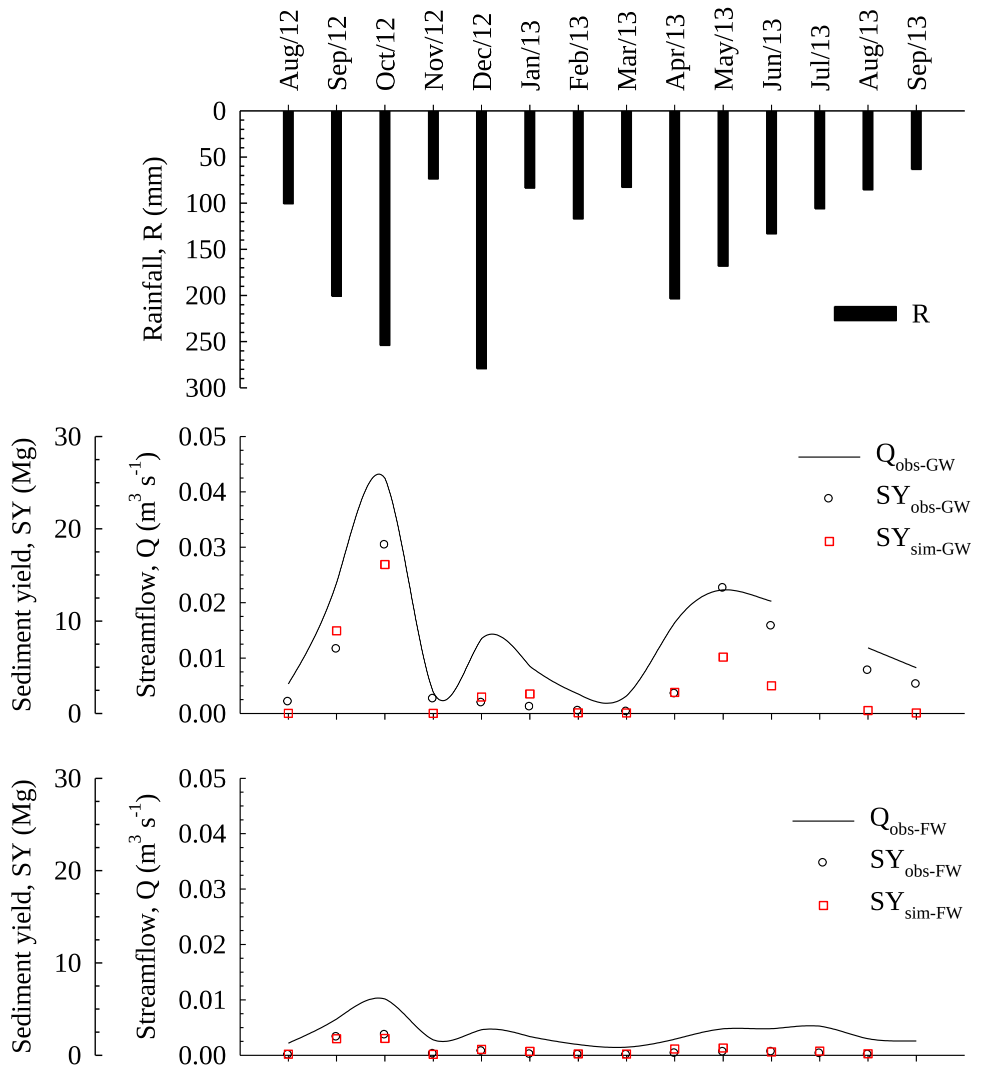

Fig. 8. Monthly rainfall (R), observed streamflow ($Q_{obs\text{-}GW}$; $Q_{obs\text{-}FW}$), and observed ($SY_{obs\text{-}GW}$) and simulated ($SY_{sim\text{-}GW}$; $SY_{obs\text{-}FW}$) sediment yield for the grassland watershed (GW) and the eucalyptus watershed (FW) outlets.

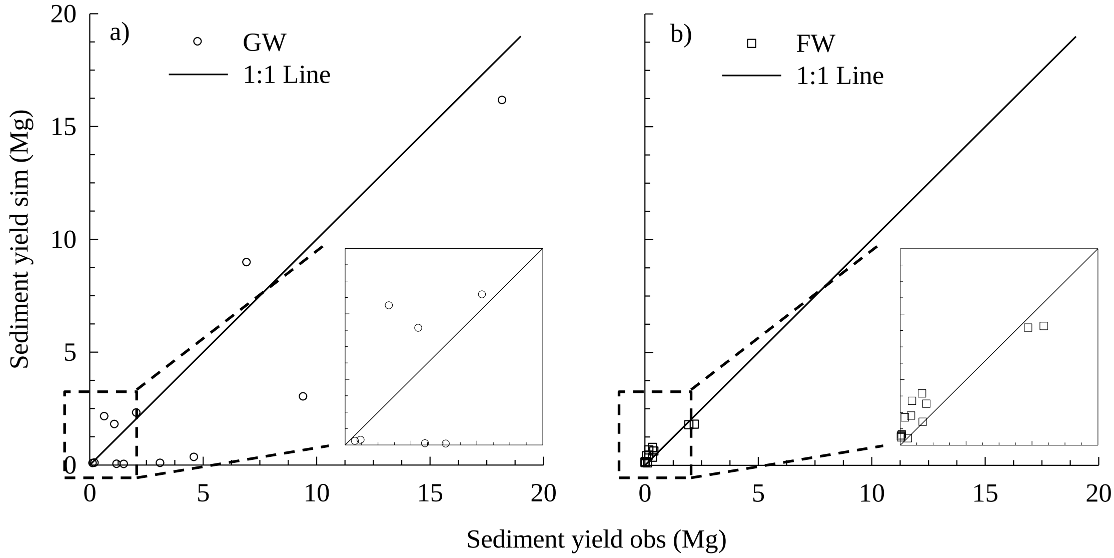

Fig. 9. Monthly dispersion diagram of observed and simulated sediment yield for the grassland watershed (GW) (a) and for the eucalyptus watershed (FW) (b) (zoom at 3 Mg). *Sim: simulated; Obs: observed.

3.3.3. Daily streamflow and sediment yield

Daily observed and simulated streamflow matched well during the calibration period for the grassland watershed and for the eucalyptus watershed (Fig. 10 and Fig. 11). Statistical parameters for the grassland watershed (NSE = 0.81 and R^2 = 0.82) and for the eucalyptus watershed (NSE = 0.85 and R^2 = 0.86) were considered "satisfactory" under our chosen standards (NSE > 0.4 and R^2 > 0.5). Streamflow was underpredicted for some periods and overpredicted for other periods for both the grassland and eucalyptus watersheds. A trend to underpredict peak flows and overpredict streamflow for hydrograph recession simulation was observed for the eucalyptus watershed but not for the grassland watershed (Fig. 12).

Statistical parameters observed for streamflow on daily time-scale, in the grassland watershed (NSE = 0.81, RSR = 0.43, and PBIAS = 13.6) and eucalyptus watershed (NSE = 0.85, RSR = 0.38, and PBIAS = 16.6), were high. If classified according to the classification proposed by Moriasi et al. (2007) for the monthly time-scale, these parameters are considered to be "very good" (NSE and RSR) and "good" (PBIAS).

Model performance for daily sediment yield was "satisfactory" for the grassland watershed and for the eucalyptus watershed during the calibration period, as indicated by NSE values of 0.78 and 0.86 (> 0.40) and R^2 values of 0.82 and 0.86 (> 0.50), respectively; even sediment yield was underpredicted in most days, but overpredicted in some days with rainfall events (Fig. 13).

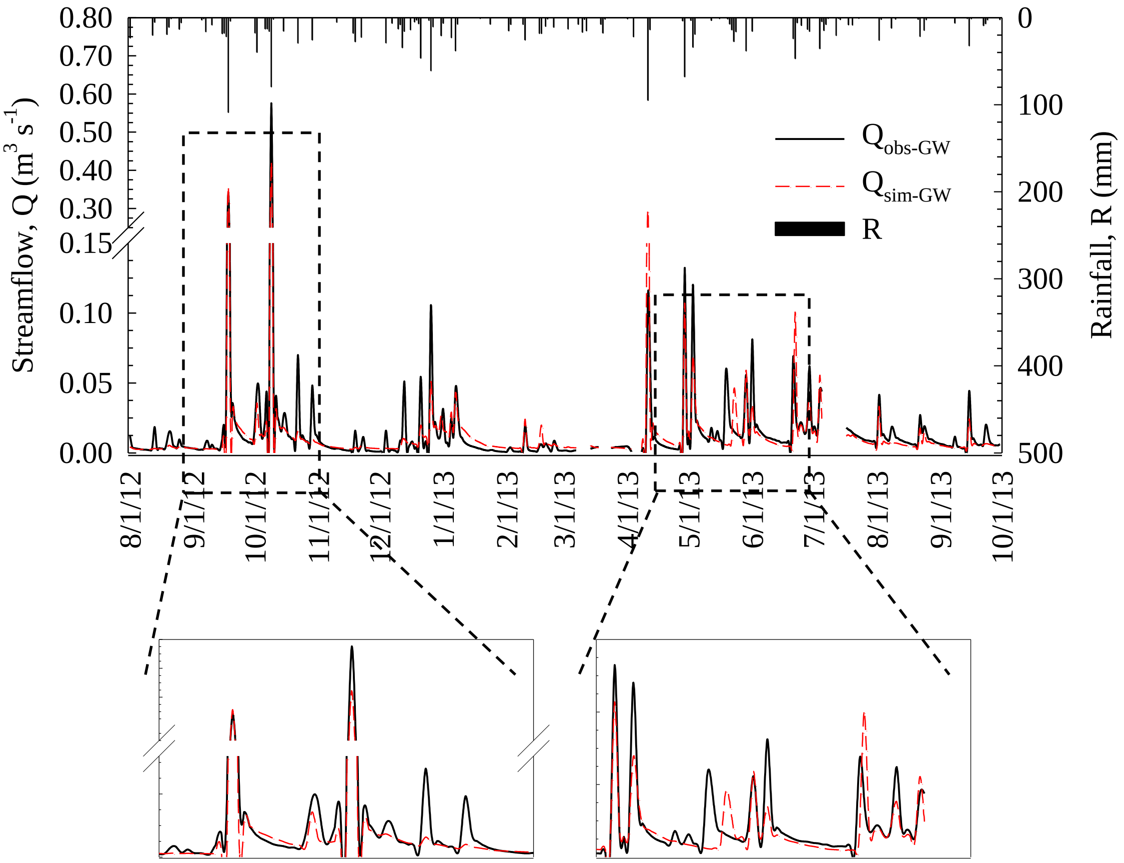

Fig. 10. Daily rainfall (R) and observed and simulated streamflow for the grassland watershed ($Q_{obs\text{-}GW}$ and $Q_{sim\text{-}GW}$) outlet (zoom at 0.60 m^3 s^{-1}: 09/05-11/10/12; zoom at 0.15 m^3 s^{-1}: 04/25-07/15/13).

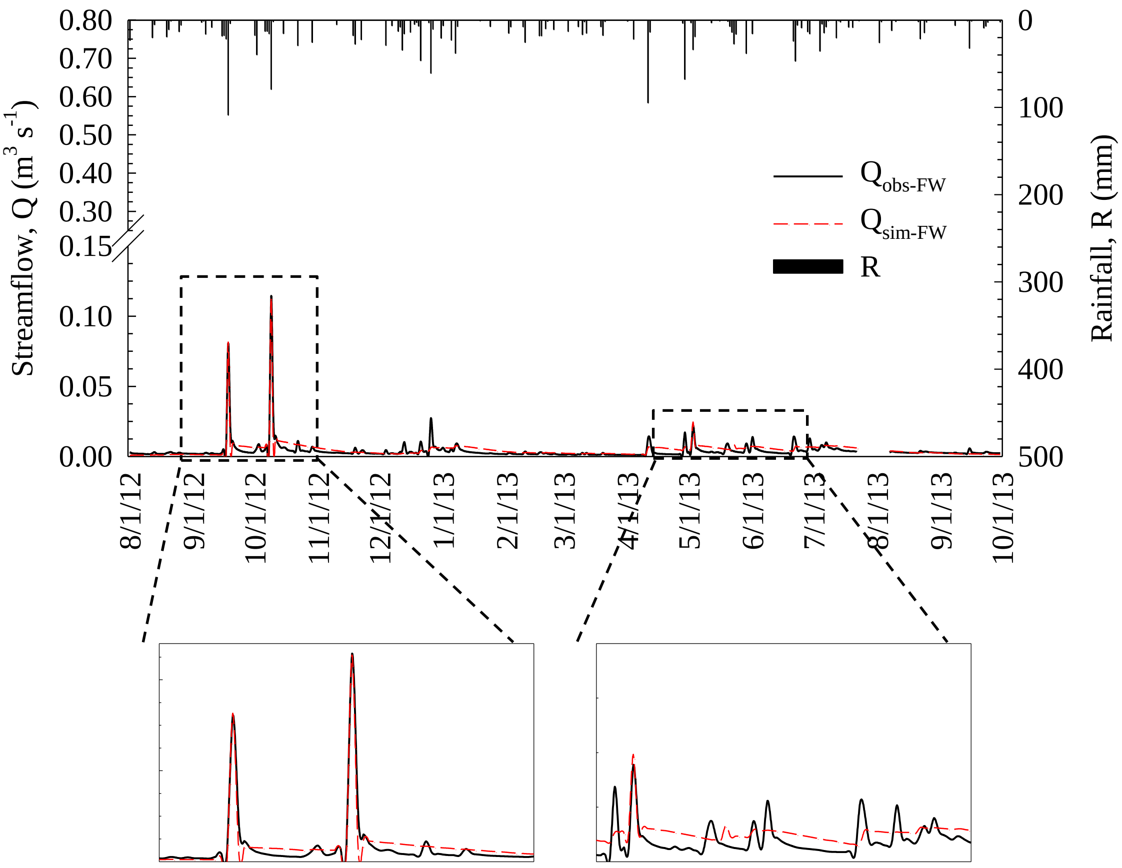

Fig. 11. Daily rainfall (R) and observed and simulated streamflow for the eucalyptus watershed ($Q_{obs\text{-}FW}$ and $Q_{sim\text{-}FW}$) outlet (zoom at 0.12 $m^3\ s^{-1}$: 09/05-11/10/12; zoom at 0.005 $m^3\ s^{-1}$: 04/25-07/15/13).

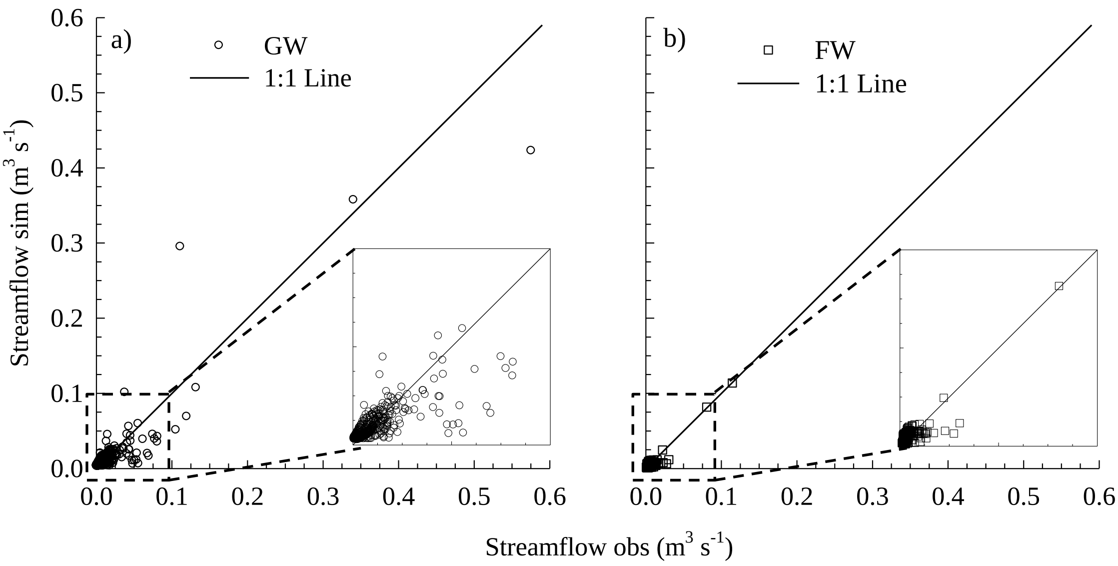

Fig. 12. Daily dispersion diagram of observed and simulated streamflow for the grassland watershed (GW) (a) and the eucalyptus watershed (FW) (b) (zoom at 0.1 m^3 s^{-1}). *Sim: simulated; Obs: observed.

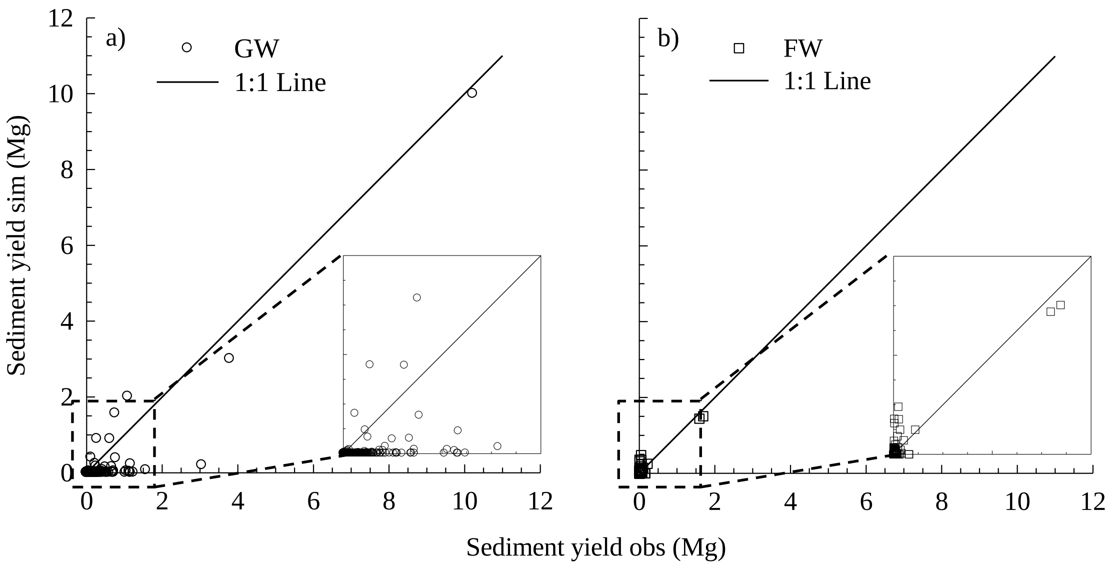

Fig. 13. Daily dispersion diagram of observed and simulated sediment yield for the grassland watershed (GW) (a) and the eucalyptus watershed (FW) (a) (zoom at 2 Mg). *Sim: simulated; Obs: observed.

3.4. Discussion

3.4.1. Sensitivity analysis

The sequence of parameter sensitivity was different between the grassland and eucalyptus watersheds. All of the sensitive parameters in our study were also the most important for the SWAT calibration phase of several other watershed studies (Cibin et al., 2010; Guse et al., 2013; Lelis et al., 2012; Meaurio et al., 2015; Oliveira, 2014; Schmalz and Fohrer, 2009; Strauch et al., 2012, 2013; Thampi et al., 2010; White and Chaubey, 2005; Zhang et al., 2011).

The most sensitive parameter for both watersheds - maximum canopy storage (CANMX) - is not the most sensitive parameter for most studies using SWAT (Lelis et al., 2012), but it does present high sensitivity in a study carried out by Fukunaga et al. (2015). The CANMX parameter influences the behavior of surface runoff. Besides the effects of the surface runoff CANMX parameter, for the grassland watershed, other parameters that influence surface runoff (SOL_ALB, SOL_AWC, SURLAG, and BLAI) and are related to groundwater (GWQMN) and channel (CH_K2) were most sensitive. For the grassland watershed, however, parameters were less sensitive than observed for the eucalyptus watershed.

Besides the effects of the surface runoff CANMX parameter, for the eucalyptus watershed, other parameters related to runoff surface (EPCO, ESCO, SOL_ALB), groundwater (GW_DELAY and RCHRG_DP), management (BIOMIX), and channel (CH_ N2) were the most sensitive. For a Brazilian watershed (2.84 km²) with eucalyptus as the major land use, Oliveira (2014) observed that CN2, CANMX, CH_K2, ALPHA_BF, SURLAG, ESCO, and CH_N2 were the most sensitive parameters, which is similar our watershed study. Results indicate that parameters sensitivity is affected by soil, land use, topography, and other physical properties of the watersheds (Lelis et al., 2012; Schmalz and Fohrer, 2009).

Soil, management, and channel parameters were the most sensitive parameters on daily time-scale for GW, while for FW the management, plant, and groundwater parameters were the most sensitive. These results indicate that parameter sensibility on daily time-scale are also affected by crops, land use, and soil management, in addition to other properties like soil, topography, and morphology.

3.4.2. Streamflow

Monthly observed and simulated streamflow matched well during the calibration period, where performance to represent streamflow was considered “good” by the NSE and RSR statistical parameters (Moriasi et al., 2007) and “very good” by the PBIAS statistical parameter (Moriasi et al., 2007) for both the grassland and eucalyptus watersheds. Our results were better than those observed by Oliveira (2014) in a forest watershed cultivated with eucalyptus stands, where calibration was considered “satisfactory”, and better than observed by Uzeika et al. (2012) in a rural watershed. Bonumá et al. (2013) obtained an NSE of 0.87 during model calibration for a rural watershed on monthly time-scale, considered to be a “very good” statistical result by Moriasi et al. (2007).

Streamflow statistic parameters were lower for monthly than daily time-scale in GW and FW. Statistical parameters observed for streamflow on daily time-scale for GW (NSE = 0.78, RSR = 0.47, and PBIAS = 69.1) and for FW (NSE = 0.86, RSR = 0.37, and PBIAS = 25.0) were high. If classified according to Moriasi et al. (2007) for monthly time-scales, these parameters are considered “very good” (NSE and RSR) for GW and “very good” (NSE and RSR) and “good” (PBIAS) for FW.

Our results differ from those observed by most researchers for different watersheds around the world (Bonumá et al., 2013; Green et al., 2006; Mishra and Singh, 2003; Setegn et al., 2010; Qiu et al., 2012; Uzeika et al., 2012), where better results are observed on monthly time-scale than daily time-scale. Results obtained by Quiao et al. (2015) agree with our results, where both daily and monthly time-scales were adequate for six paired experimental watersheds (three for grassland and three for forest encroached grassland). They observed that statistical values indicate that the model performed well not only on monthly time-scale but also on daily time-scale, where NSE and R^2 were high (NSE = 0.90 and R^2 = 0.90) on daily time-scale for forest watersheds and for grassland watersheds (NSE = 0.96 and R^2 = 0.96).

Adequate representation of hydrograph recession was observed, especially for GW, which probably provided better results for daily than monthly time-scale in our study. For GW we observed underprediction of most peak flows and a good representation of hydrograph recession, while for FW we observed good representation of peak flows for only two higher-intensity events, and underpredicted representation of peak flow for other events as well as overprediction of hydrograph recession. Bonumá et al. (2013) observed underprediction for low flows on daily time-scale due to inadequacy of the hydrograph recession simulations, similar to the observed in our study, and partly due to measurement errors.

Underprediction of peak flows and overprediction of hydrograph recession occurs because peak flows are more sensitive to variations due to rainfall intensity and antecedent soil moisture content (Moriasi et al., 2007) while the recession curves are affected by the baseflow component (Bonumá et al., 2013). SWAT's uncertainties of hydrograph representation could be attributed to its dependence on many empirical and semi-empirical models, such as SCS-CN and MUSLE, which causes SWAT to track specific peak runoff and sediment load less accurately. These findings have implications for modifying the model to take the rainfall intensity and its duration into account to enhance model accuracy for peak flow and sediment load simulation when the model is applied to flood prediction (Qiu *et al*., 2012).

Furthermore, the results indicate "satisfactory" model performance at the watershed outlet for small watersheds on monthly and daily time-scales depends on land use and climate conditions. Watershed physical properties (size, relief, soil type) affect hydrosedimentological processes in the watershed, and limited knowledge about these properties may negatively impact performance of the SWAT model. Uncertainty due to input data scarcity and short time period of monitored data affect parameter values (Bonumá et al., 2013). Surface and baseflow processes will be ill-represented if a parameter value does not adequately represent a process. Bieger et al. (2015) highly recommend evaluation of model output in small areas like at the HRU level. In our study, results of simulations and observed and simulated behavior of hydrological and sedimentological processes indicate that land use has important effects for both monitored and simulated processes.

Therefore, SWAT requires improvement to adequately to simulate processes for forested small watersheds, and the model needs to be evaluated in scales at which processes occur, especially at HRU scale for paired watersheds with different land uses and on sub-daily time-scale to adequately represent the hydrological processes.

3.4.3. Sediment yield

The model effectively simulated monthly and daily sediment yield for GW and FW. During the studied period, SWAT model simulation on monthly time-scale underpredicted sediment yield for some months and overpredicted it for others, while sediment yield was underpredicted for most periods on daily time-scale.

Model performance was "satisfactory" in general for GW and "very good" for FW at the monthly time-scale (Moriasi et al., 2007). Statistical parameters for sediment yield prediction on daily time-scale were better than monthly time-scale for GW, similar to FW.

Statistical parameters observed for sediment yield on daily time-scale for GW (NSE = 0.78 and R^2 = 0.82) and FW (NSE = 0.86 and R^2 = 0.86) were high. If classified according to Moriasi et al. (2007) for the monthly time-scale, these parameters are classified as “very good”.

We obtained “satisfactory” statistical indicators for sediment yield prediction, contrary to the results obtained by Bonumá et al. (2013) and Uzeika et al. (2012) in small agricultural watersheds in Southern Brazil; however, the results may not represent where erosion processes in fact occur, especially those in the stream channel. These two studies overpredicted sediment yield using the SWAT model. Uzeika et al. (2012) observed SWAT was unable to adequately predict daily and monthly sediment yield for each evaluated year, and SWAT significantly overpredicted sediment yield for both time-scales for a small watershed (1.19 km^2).

Unfavorable simulation results for agricultural watersheds may be caused by limitations in the sediment load equation (MUSLE) or sediment propagation in channel. Sediment deposition was held responsible for the overprediction of sediment yield, especially in watersheds with intensive agriculture and riparian vegetation, since large volumes of sediment were deposited in depressions in fields near to the alluvial channel, thus indicating that not all eroded soil on hillslopes reaches the stream (Bonumá et al., 2013; Bonumá et al., 2015; Uzeika et al., 2012).

Our results indicate that sediment yield was mostly underpredicted. SWAT sediment load underprediction could be attributed to model dependence on many empirical and semi-empirical models, such as SCS-CN and MUSLE, which caused SWAT to track specific peak runoff and sediment load less accurately. These findings had indicate a need for modifying the model to take the rainfall intensity and its duration into account to enhance model accuracy for peak flow and sediment load simulation when the model is applied to flood prediction (Qiu et al., 2012).

Sediment loss is likely more affected by land management practices (USLE_P factor) than by slope since the watersheds (GW and FW) have smooth relief. Therefore, absence of tillage and soil protection during the eucalyptus cycle in FW or maintenance of grassland in GW may have contributed to sediment yield underprediction in our study, when compared to intensive agriculture on steeps slopes that have overpredicted sediment yields (Bonumá et al., 2013). Furthermore, our study had a short period of monitoring and conclusive data should be obtained with longer period of monitoring.

3.5. Conclusions

Streamflow and sediment yield in paired grassland and eucalyptus watersheds in the Pampa Biome were well simulated by the SWAT ecohydrological model. The model provided better results for daily than monthly time-scale.

Prediction of sediment yield was efficient on both monthly and daily time-scales for grassland and eucalyptus watersheds. Sediment yield was underpredicted, possibly due to model dependence on many empirical and semi-empirical equations, which may have forced SWAT to accurately track specific peak runoff and sediment load less.

Calibrated SWAT model results are very encouraging for hydrological and sedimentological processes simulation in grassland and eucalyptus paired-watersheds in the Pampa Biome. The model successfully and consistently reproduced streamflow and sediment yield in the paired watersheds. Furthermore, considering the uncertainties in model representation it is necessary to simulate the processes on sub-daily time-scale, especially in small watersheds where processes occur in less than one day.

To properly understand spatial and temporal variations in hydrological and sedimentological processes in small grassland and forest watersheds more field work is required, besides time and effort to calibrate the SWAT model for different land uses in grasslands undergoing land use change, such as in the Pampa Biome.

3.6. References

Abbaspour, K.C., 2007. SWAT-CUP: SWAT calibration and uncertainty programs – A user manual, 100p.

Abbaspour, K.C., Johnson, C.A., van Genuchten, M.Th., 2004. Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure. Vadose Zone J. 3, 1340-1352.

Abbaspour, K.C., Vejdani, M., Haghighat, S., 2007. SWAT-CUP calibration and uncertainty programs for SWAT, In: Congress on Modeling and Simulation, Melbourne, Australia, 2007. Melbourne, Australia, Modeling and Simulation Society of Australia and New Zealand, 1603-1609.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M., Sparovek, G., 2013. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift 22,711-728.

Andréassian, V., 2004. Waters and forests: from historical controversy to scientific debate. J. Hydrol. 291, 1-27.

Arnold, J.G., Fohrer, N., 2005. SWAT2000: Current capabilities and research opportunities in applied watershed modeling. Hydrol Process. 19, 563-572.

Arnold, J.G., Kiniry, J.R., Srinivasan, R., Williams, J.R., Haney, E.B., Neitsch, S.L., 2012. Soil & Water Assesment Tool: Input/output documentation – version 2012.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment. Part I: Model development. J. Am. Water Resour As. 34, 73-89.

ASSOCIAÇÃO BRASILEIRA DOS PRODUTORES DE FLORESTAS PLANTADAS (ABRAF), 2013. Anuário estatístico da ABRAF 2013 ano base 2012. ABRAF: Brasília, 148 p.

ATLAS SOCIOECONÔMICO DO RIO GRANDE DO SUL, 2011. Available at: <http://www.scp.rs.gov.br/atlas>. Access in: 28 sep. 2012.

Baumhardt, E., 2010. Balanço Hídrico em Microbacia Sob Influência da Silvicultura do Eucalyptus em Região do Biome Pampa. (Master Thesis), Engenharia Civil. Universidade Federal de Santa Maria, Brazil.

Baumhardt, E., 2014. Hidrologia de bacia de cabeceira com eucaliptocultura e campo nativo na região da campanha gaúcha. (Doctoral Thesis), Engenharia Florestal. Universidade Federal de Santa Maria, Brazil.

Bieger, K., Hormann, G., Fohrer, N., 2015. Detailed spatial analysis of SWAT-simulated surface runoff and sediment yield in a mountainous watershed in China. Hydrolog. Sci. J. 60, 784-800.

Bonumá NB, Rossi CG, Arnold JG, Reichert JM, Paiva EMCD. 2012. Hydrology evaluation of the Soil and Water Assessment Tool considering measurement uncertainty for a small watershed in Sourthen Brazil. Appl. Eng. Agric. 29:189-200.

Bonumá, N.B., 2011. Modelagem do escoamento, da produção de sedimentos e da transferência de fósforo em bacia rural no sul do Brasil. (Doctoral Thesis), Ciência do Solo. Universidade Federal de Santa Maria, Brazil.

Bonumá, N.B., Reichert, J.M., Rodrigues, M.F., Monteiro, J.A.F., Arnold, J.G., Srinivasan, R., 2015. Modeling surface hydrology, soil erosion, nutrient transport, and future scenarios with the ecohydrological SWAT model in Brazilian watersheds and river basins. In: Nascimento CWA, Souza Júnior VS, Freire MBGS, Souza ER (Org.). Tópicos em Ciência do Solo, IX:241-290.

Bonumá, N.B., Rossi, C.G., Arnold, J.G., Reichert, J.M., Minella, J.P.G., Allen, P.M., Volk, M., 2013. Simulating landscape sediment transport capacity by using a modified SWAT Model. J. Environ. Qual. 43, 55-66.

Borah, D.K., Yagow, G., Saleh, A., Barnes, P.L., Rosenthal, W., Krug, E.C., Hauck, L.M., 2006. Sedimentation and nutrient modeling for TMDL development and implementation. T. ASABE 49, 967-986.

Bressiani, D.A., Gassman, P.W., Fernandes, J.G., Garbossa, L.H.P., Srinivasan, R., Bonumá, N.B., Mendiondo, E.M., 2015. Review of Soil and Water Assessment Tool (SWAT) applications in Brazil: Challenges and prospects. Int. J. Agric. Biol. Eng. 8, 9-35.

Calder, I.R., 2007. Forests and water: ensuring forest benefits outweigh water costs. Forest Ecol. Manag. 251, 110-120.

Cibin, R., Sudheer, K.P., Chaubey, I., 2010. Sensitivity and identifiability of stream flow generation parameters of the SWAT model. Hydrol. Process. 24, 1133-1148.

Denardin, J.E., 1990. Erodibilidade de solo estimada por meio de parâmetros físicos e químicos. (Doctoral Thesis). Escola Superior de Agricultura Luiz de Queiroz da Universidade de São Paulo, Brazil.

Edwards, T.K., Glysson, G.D., 1998. Field methods for measurement of fluvial sediment. US Geological Survey Open-File Report 86-531. 118p.

EMBRAPA – Empresa Brasileira de Pesquisa Agropecuária, 2006. Sistema Brasileiro de Classificação de Solos. Brasília: Embrapa. 306p.

Evans, J., Turnbull, J.W., 2004. Plantation forestry in the tropics: the role, silviculture, and use of planted forests for industrial, social, environmental, and agroforestry purposes. 480p.

Ferreira, A.G., Gonçalves, A.C., Dias, S.S., 2008. Avaliação da Sustentabilidade dos Sistemas Florestais em Função da Erosão. Silva Lusitana 16, 55-67.

Fukunaga, D.C., Cecílio, R.A., Zanetti, S.S., Oliveira, L.T., Caiado, M.A.C., 2015. Application of the SWAT hydrologic model to a tropical watershed at Brazil. Catena 125, 206-213.

Green, C.H., Tomer, M.D., Di Luzio, M., Arnold, J.G., 2006. Hydrologic evaluation of the Soil and Water Assessment Tool for a large tile-drained watershed in Iowa. T. ASABE 49, 413-422.

Green, C.H., van Griensven, A., 2008. Autocalibration in hydrologic modeling: Using SWAT2005 in small-scale watersheds. Environ. Modell. Softw. 23, 422-434.

Guse, B., Reusser, D.E., Fohrer, N., 2013. How to improve the representation of hydrological processes in SWAT for a lowland catchment - temporal analysis of parameter sensitivity and model performance. Hydrol. Process. 28, 2651-2670.

Guy, H.P., 1969. Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations. Washington, DC, C1 US Government Printing Office, v.5. 58p.

Hargreaves, G., Samani, Z.A., 1985. Reference crop evapotranspiration from temperature. T. ASAE 1, 96-99.

Lelis, T.A., Calijuri, M.L., Santiago, A.F., Lima, D.C., Rocha, E.O., 2012. Análise de sensibilidade e calibração do modelo SWAT aplicado em bacia hidrográfica da região sudeste do Brasil. R. Bras. Ci. Solo 36, 623-634.

Lima, W.P., 2005. Planted forests and water impacts: cross-scale analysis through hydrological indicators. The International Forestry Review 7, 758-764.

Meaurio, M., Zabaleta, A., Uriarte, J.A., Srinivasan, R., Antigüedad, I., 2015. Evaluation of SWAT models performance to simulate streamflow spatial origin. The case of a small forested watershed. J. Hydrol. 525, 326-334.

Mishra, S.K., Singh, V.P., 2003. Soil Conservation Service Curve Number (SCS-CN) Methodology. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Molchanov, A.A., 1963. The hydrological role of forests. 407pp.

Morales, B.P., 2013. Atributos do solo e produtividade de *Eucalyptus saligna* e *Eucalyptus dunni* no Sul do Rio Grande do Sul. (Master Thesis), Engenharia Florestal. Universidade Federal de Santa Maria, Brazil.

Moreno, J.A., 1961. Clima do Rio Grande do Sul. Secretaria da Agricultura. Porto Alegre, 73p.

Moriasi, D.N., Arnold, J.G., van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. T. ASABE 50, 885-900.

Oki, T., Kanae, S., 2006. Global hydrological cycles and world water resources. Science, 313, 1068-1072.

Oliveira, A.H., 2011. Erosão hídrica e seus componentes na sub-bacia hidrográfica do horto florestal Terra Dura, Eldorado do Sul (RS). (Doctoral Thesis) Engenharia Florestal. Universidade Federal de Lavras, Brazil.

Oliveira, L.T., 2014. Aplicação do modelo SWAT para simular vazões em uma bacia hidrográfica em Aracruz, ES. (Master Thesis), Ciências Florestais. Universidade Federal do Espírito Santo, Brazil.

Porto, P., Walling, D.E., Callegari, G., 2009. Investigating the effects of afforestation on soil erosion and sediment mobilization in two small catchments in Southern Italy. Catena 79, 181-188.

Post, D.F., Fimbres, A., Matthias, A.D., Sano, E.E., Accioly, L., Batchily, A.K., Ferreira, L.G., 2000. Predicting soil albedo from soil color and spectral reflectance data. Soil Sci. Soc. Am. J. 64, 1027-1034.

Qiu, L., Zheng, F., Yin, R., 2012. SWAT-based runoff and sediment simulation in a small watershed, the loessial hilly-gullied region of China: capabilities and challenges. Int. J. Sed. Res. 27, 226-234.

Qiao, L., Zou, C.B., Will, R.E., Stebler, E., 2015. Calibration of SWAT model for woody plant encroachment using paired experimental watershed data. J. Hydrol. 523, 231-239.

Ramgrab, G.E., Wildner, W., Lopes, R.C., Favilla, C.A.C., Silva, M.A.S., Sachs, L.L.B., Silva, V.A., Batista, I.H., 2004. Folha SH.22 – Porto Alegre. In: Schobbenhaus C, Gonçalves JH, Santos JOS, Abram MB, Leão Neto R, Matos GMM, Vidotti RM, Ramos MAB, Jesus JDA. (Eds.) Carta Geológica do Brasil ao Milionésimo, Sistema de Informações Geográficas. Programa Geologia do Brasil. Brasília, CPRM. Available in: <http://www.cprm.gov.br/publique/cgi/cgilua.exe/sys/start.htm?infoid=298&sid=26>.

Ranzini, M., Lima, W.P., 2002. Comportamento hidrológico, balanço de nutrientes e perdas de solo em duas microbacias reflorestadas com Eucalyptus, no Vale do Paraíba, SP. Scientia Forestalis 61, 144-159.

Santhi, C., Arnold, J.G., Williams, J.R., Dugas, W.A., Srinivasan, R., Hauck, L.M., 2001. Validation of the SWAT model on a large river basin with point and nonpoint sources. J. Am. Water Res. As. 37, 1169-1188.

Schmalz, B., Fohrer, N., 2009. Comparing model sensitivities of different landscapes using the ecohydrological SWAT model. Adv. Geosc. 21, 91-98.

Schoenholtz, S.H., Miegroet, H., Burger, J.A., 2000. A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities. Forest Ecol. Manag. 138, 335-356.

Setegn, S.G., Srinivasan, R., Melesse, A.M., Dargahi, B., 2010. SWAT model application and prediction uncertainty analysis in the Lake Tana Basin, Ethiopia. Hydrol. Process. 24, 357-367.

Sheridan, G.J., Noske, P.J., Whipp, R.K., Wijesinghe, N., 2006. The effect of truck traffic and road water content on sediment delivery from unpaved forest roads. Hydrol. Process. 20, 1683-1699.

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. T. Am. Geophys. Un. 38, 913-920.

Strauch, M., Bernhofer, C., Koide, S., Volk, M., Lorz, C., Makeschin, F., 2012. Using precipitation data ensemble for uncertainty analysis in SWAT streamflow simulation. J. Hydrol. 414, 413-424.

Strauch, M., Lima, J.E., Volk, M., Lorz, C., Makeschin, F., 2013. The impact of best management practices on simulated streamflow and sediment load in a Central Brazilian catchment. J. Environ. Manag. 127, S24-S36.

Strauch, M., Volk, M., 2013. SWAT plant growth modification for improved modeling of perennial vegetation in the tropics. Ecol. Modell. 269, 98-112.

Streck, C., Scholz, S.M., 2006. The role of forests in global climate change: whence we come and where we go. Int. Aff. 82, 861-879.

Thampi, S.G., Raneesh, K.Y., Surya, T.V., 2010. Influence of scale on SWAT model calibration for streamflow in a river basin in the humid tropics. Water Resour. Manag. 24, 4567-4578.

USDA - United States Department of Agriculture. 1999. Soil Survey Staff. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. 2nd ed. U.S. Department of Agriculture/Natural Resources Conservations Service, Washington, Agriculture Handbook. 871pp.

Uzeika, T., Merten, G.H., Minella, J.P.G., Moro, M., 2012. Use of the SWAT model for hydro-sedimentologic simulation in a small rural watershed. R. Bras. Ci. Solo 36, 557-565.

Van Dijk, A.I.J.M., Hairsine, P.B., Arancibia, J.P., Dowling, T.I., 2007. Reforestation, water availability and stream salinity: a multi-scale analysis in the Murray-Darling Basin, Australia. Forest Ecol. Manag. 251, 94-109.

Van Dijk, A.I.J.M., Keenan, R., 2007. Planted forests and water in perspective. Forest Ecol. Manag. 251, 1-9.

van Griensven, A., Meixner, T., Grunwald, S., Bishop, T., Di Luzio, M., Srinivasan, R., 2006. A global sensitivity analysis tool for the parameters of multi-variable catchment models. J. Hydrol. 324, 10-23.

Vanclay, J.K., 2009 Managing water use from forest plantations. Forest Ecol. Manag. 257, 385-389.

Vital, A.R.T., Lima, W.P., Camargo, F.R.A., 1999. Efeitos do corte raso de plantação de Eucalyptus sobre o balanço hídrico, a qualidade da água e as perdas de solo e de nutrientes em uma microbacia no Vale do Paraíba, SP. Scientia Forestalis 55, 5-16.

White, K.L., Chaubey, I., 2005. Sensitivity analysis, calibration, and validations for a multisite and multivariable swat model. J. Am. Water Resour. Assoc. 41, 1077-1089.

Wu, Y., Chen, J., 2009. Simulation of nitrogen and phosphorus loads in the Dongjiang River basin in South China using SWAT. Front. Earth Sci. China 3, 273-278.

Zhang, X., Srinivasan, R., Arnold, J., Izaurralde, R.C., Bosch, D., 2011. Simultaneous calibration of surface flowand baseflow simulations: a revisit of the SWAT model calibration framework. Hydrol. Process. 25, 2313-2320.

4 ARTICLE III: SEDIMENT FINGERPRINTING IN NESTED WATERSHEDS CROPPED TO EUCALYPTUS AND RIPARIAN FOREST

Abstract

Forests provide surface litter and canopy for partial soil protection and erosion control, where sediments represent environment degradation. Identifying sediments sources in a watershed is essential to accurately target management actions designed to reducing sediment delivery to water bodies. We examine the effect of two particle sizes and location of potential sediment sources on their contribution to sediment yield. Geochemical properties, determined by inductively coupled plasma mass spectrometry and X-ray fluorescence analyses, were employed to calculate proportional contributions of sediment in a watershed (0.98 km^2) and in a sub-watershed (0.39 km^2) cropped to commercial eucalyptus by using sediment fingerprinting approach. The sediment-sources evaluated were eucalyptus stand, stream bank and unpaved roads. Source contributions were determined at points spatially distributed sites along the main channel of the watershed. Source determination for in-stream sites was done using samples collected at one spot to evaluate source-contribution of area upstream of this site of interest, to indicate how different sources dominate at different locations downstream. To examine whether different size fractions shared similar origins, two size fractions of both source and suspended samples including fine (<0.063 mm) and coarse (0.063–2 mm) particles were analyzed. The source apportionment results using the distribution mixing model indicate particle-size and location of sources within a watershed are major factors affecting the contribution of sediment-sources for coarse and fine sediments. The closer the sediment-source, the higher was the sediment source contribution, especially for coarse particles. The relative contribution of each source to sediment yield was bank, i.e., from the stream network. These results indicate that management actions should be focused on the channel rather than on areas with eucalyptus or riparian vegetation.

Keywords: Soil erosion; Sediment yield; Sediment sources; Scale effect; Size fraction; Geochemical properties.

4.1. INTRODUCTION

The expansion of forest production areas with fast-growing species, especially eucalyptus, is a response to the increased demand for forest products. The effects of *Eucalyptus* spp. Forests are not well known and there are uncertainties about the ability of production land to support planted forests without degrading water and land resources (Rodrigues *et al*., 2014). Further, studies on sediment generation and contribution of each source to total sediment yield are incipient. Proper identification of sediment sources contribute to the efficiency of a forest production system in maintaining the quality of natural resources, the management of resources, and the establishment of proper use and management techniques, to limit or reduce degradation, especially on watershed scale.

Contribution of sediment-producing sources to total sediment yield has been investigated predominantly in agricultural watersheds (Smith *et al*., 2015) with evidence of erosion and sediment deposition (Minella *et al*., 2007, 2008, 2009a, 2009b; Tiecher *et al*., 2014, 2015a), and deforestation to prepare land to agriculture production (Bai *et al*., 2013), or in forest areas harvested and site prepared for new planting (Schuller *et al*., 2013). However, information about sediment-producing sources is incipient in areas of forestry production along the cultivation cycle. For instance, eucalyptus stands may control runoff, reduce peak flow (Mello *et al*., 2007), and this reduce soil and nutrients losses. This control becomes more efficient as forest stand develops (Lima, 1990).

In river basins or watersheds comprised mainly with cultivated forest stands, the main source of sediment yield may not be forest due to the ability of forest canopy to protect the land from erosion. As watershed-scale processes are dynamic and complex, the effects of erosion can be minimized with the cultivation of planted forests and/or transferred to other land uses in watershed sites, and may be observed more frequently in drainage and roads network. Thus, reducing the sediment yield or changing the contribution of each sediment-source. Each sediment-source has different characteristics in magnitude of contribution and potential contamination, whereas identifying sediment sources is critical in understanding sediment emission rate and in management of sediments eroded at the watershed scale (Minella *et al*., 2007).

Physico-chemical properties of eroded sediment have close relationship with soil and sediments from different sources within a watershed. Thus, the use of natural tracers by means of geochemical composition analysis of soil and sediment, in statistical methods with "fingerprinting" technique, allows to quantifying the contributions of the main sources of sediment yield to the global sediment (D’ Haen *et al*., 2012). Fingerprinting is based on the principle that suspended sediment properties maintain their source geochemical properties, which may thus be used as tracers (Minella *et al*., 2007; Minella *et al*., 2009a).

Suspension (Bilotta and Brazier, 2008; Haddadchi *et al*., 2015; Owens *et al*., 2005) and bed load sediment transported cause various environmental problems (Bilotta and Brazier, 2008; Haddadchi *et al*., 2015; Owens *et al*., 2005). Studies in watersheds under agricultural production, using fingerprinting technique for source identification of sediment transported in suspension have been conducted successfully in several countries and have been expanding rapidly (Smith *et al*., 2015; Walling *et al*., 2013). In Southern Brazil, studies were carried out in small rural watersheds, in sloping areas cropped mainly with tobacco in small family-farm units (Minella *et al*., 2007; Minella *et al*., 2008; Minella *et al*., 2009a; Minella *et al*., 2009b; Tiecher *et al*., 2015a; Tiecher *et al*., 2015b), in areas with predominance of annual crops under no-tillage system (Tiecher *et al*., 2014), and on hillsides where shallow soils and non-intensive agriculture predominate (Miguel *et al*., 2014a; Miguel *et al*., 2014b), and for urban watersheds (Poleto *et al*., 2009; Franz *et al*., 2014). For all these agricultural (Miguel *et al*., 2014a; Minella *et al*., 2007; Minella *et al*., 2008; Minella *et al*., 2009a; Minella *et al*., 2009b; Tiecher *et al*., 2014), the fingerprinting was effective in indicating crops and roads were the main sources of suspended sediment transported.

Identification of coarser-sediment sources has received very little attention. Furthermore, for the correct identification of sediment sources we should consider the proportion of individual sources to the sediment mixture, where sediment type and size distribution is variable in time and space as a result of erosive processes in the watershed (Minella *et al*., 2009a) and of rock-type sources (Haddadchi *et al*., 2015) and processes of soil formation.

Different sediment-size fractions have distinct negative effects on water networks, thus requiring a myriad of strategies to erosion control avoiding thus soil and water degradation. Coarse-sediment fractions may only be transported to higher distances during high flow events or very short distances during low flow, whilst finer fractions are transported to long distances in low intensity and energy flow events. Erosion processes are size-selective during the supply, transport and storage steps of sediment movement (Koiter *et al*., 2013). Several factors, including flow condition, soil aggregation, soil type, erosion type and rainfall parameters, affect the degree of selectivity in a particular watershed (Haddadchi *et al*., 2015).

Sediments and potential sources with different particle-sizes were used in previous sediment fingerprinting studies (Foster *et al*., 2007; Fox and Papanicolaou, 2007; Collins *et al*., 2010; Devereux *et al*., 2010; Fukuyama *et al*., 2010; Evrard *et al*., 2011; Blake *et al*., 2012; Caitcheon *et al*., 2012; Collins *et al*., 2012; Navratil *et al*., 2012; Poulenard *et al*., 2012; Smith *et al*., 2012; Evrard *et al*., 2013; Olley *et al*., 2013; Palazón *et al*., 2015) after the particle size correction using a correction factor, whilst sources of three different size-fractions were evaluated for suspended sediment in a water supply whatershed in one study (Haddadchi *et al*., 2015).

Nevertheless, there are no studies that evaluated fine (suspended) and coarse-size fractions. Sources of different sediment-size fractions may vary because of different entrainment processes and transport characteristics. Consequently, depending on the particular process is a given watershed, the size-fraction used in tracing study to identify the primary sources needs to be carefully selected (Haddadchi *et al*., 2015).

Most of the sediment which enters the system does not get transported all the way to the watershed outlet (Caitcheon *et al*., 2012), and thus sediment yield at the outlet of a watershed represents a small portion of the total sediment produced in the watershed as a result of all operative erosion processes (Minella *et al*., 2014; Rodrigues *et al*., 2014). Small watersheds show sediment deposition on footslopes, floodplains (Bonumá *et al*., 2013) and within channels (Prosser *et al*., 2001).

We aimed to apply a sediment source fingerprinting procedure to discriminate sources for two different size fractions of sediment (< 0.063 mm and 0.063-2 mm) deposited along drainage network, and suspended sediment from flow events collected at watershed outlet in a small watershed with eucalyptus plantation.

4.2. MATERIALS AND METHODS

4.2.1. Area of study

The study was done in the Terra Dura Forestry Watershed, comprised of two watersheds - main and nested, both under forest cover and located in the Jacuí River Basin, located in the physiographic region of Central Depression in Rio Grande do Sul State, Southern Brazil (Figure 1). The whole watershed (0.98 km^2) is herein called "watershed", whereas the nested watershed (0.39 km^2) is named "sub-watershed".

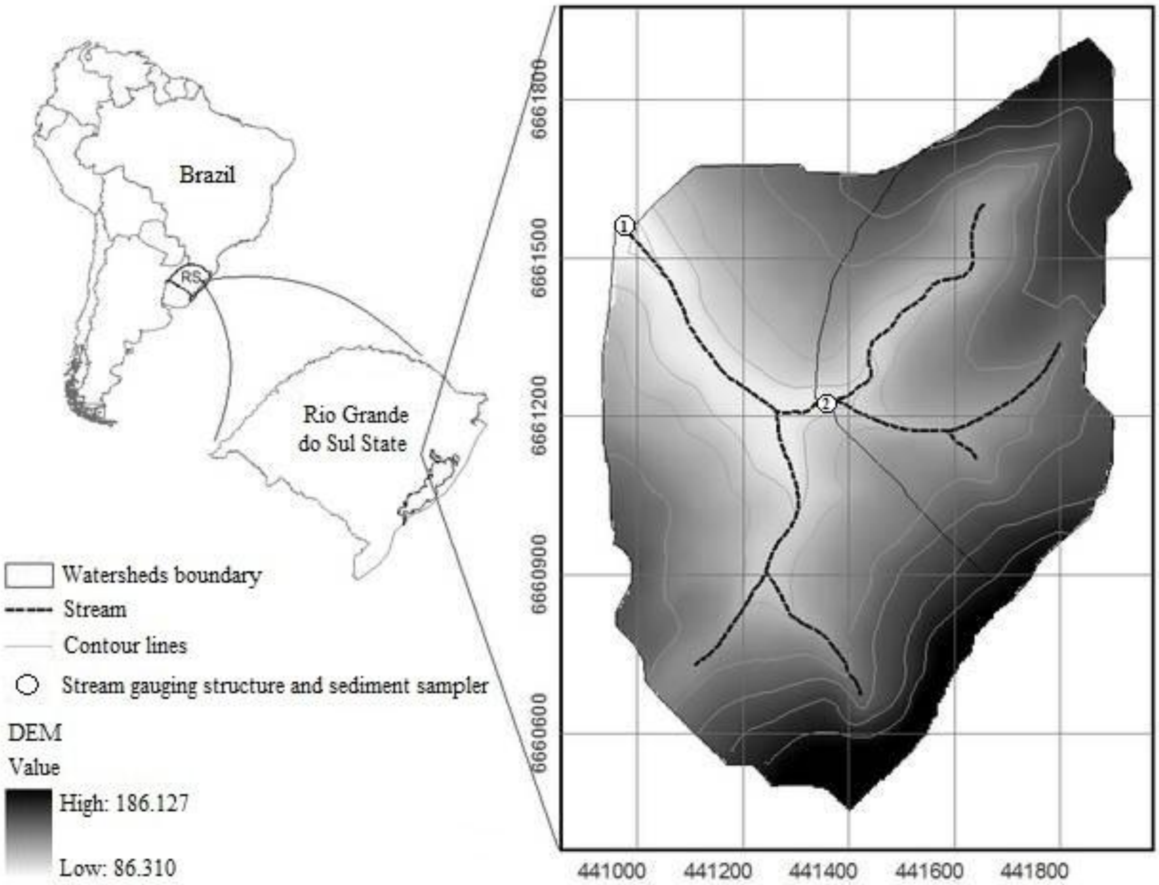

Figure 1. Location and slope isolines for the studied forest watershed (1) and sub-watershed (2), in Eldorado do Sul-RS, Southern Brazil.

Climate is Cfa - humid subtropical with hot summers, according to the Köppen climatic classification (Alvares *et al*., 2013). Average annual rainfall is 1440 mm, monthly average of 120 mm, and months with more rainfall are from June to August, both in rainfall volume and duration and number of rainy days (Bergamaschi *et al*., 2003; Bergamaschi *et al*., 2013). Average long-term erosivity for the region is 5813 MJ ha^{-1} mm^{-1}, calculated with the equation proposed by Lombardi Neto and Moldenhauer (1992) and Silva (2004).

Geology consists of intrusive igneous rocks, syenogranites corresponding to Intrusive Suíte Dom Feliciano - Lithofacies Serra do Herval, Neoproterozoic period (2500 Ma) (Ramgrab *et al*., 2004). Soils on site are classified as *Argissolo Vermelho*, *Argissolo Amarelo*, *Argissolo Vermelho-Amarelo*, *Cambissolo Háplico*, and *Planossolo Háplico* (Costa *et al*., 2009, Brazilian Soil Classification System - Embrapa, 2006), and as Ultisols, Inceptisols and Planosols (Soil Taxonomy - USDA, 1999). Soil texture gradient is greater in Ultisols and Planosols (Oliveira, 2011), where the sandy texture in surface horizons (A + E) provides rapid water infiltration, which decreases inside the textural B horizon due to its lower permeability. Subsurface discharge often removes soil particles forming channels called pipes.

Land use data over the study period were determined by field surveys, assisted by a geographic positioning system with GIS software and checked in Google Earth®. The predominant land use consists of commercial forest cultivated with eucalyptus stand (planted in 1990 (6.4%), 2001 (17.0%), 2004 (38.9%), 2005 (4.2%), and 2010 (10.6%)); permanent preservation areas (PPA), i.e., riparian native vegetation (20.9%); and unpaved roads (2.1%) (Figure 2).Soil cover in young stands is provided by grasses and legumes species that grow between tree rows, and in old stands is provided by undergrowth or litter layer, which provides partial soil surface protection against the effects of soil erosion agents.

The watershed and sub-watershed are characterized by a drainage network of third and second order (Strahler, 1957), respectively. The second and third order channels have deposits of coarse sediments (sand and gravel), whilst the margins of these channels are composed of sandy material and are very susceptible to water erosion.

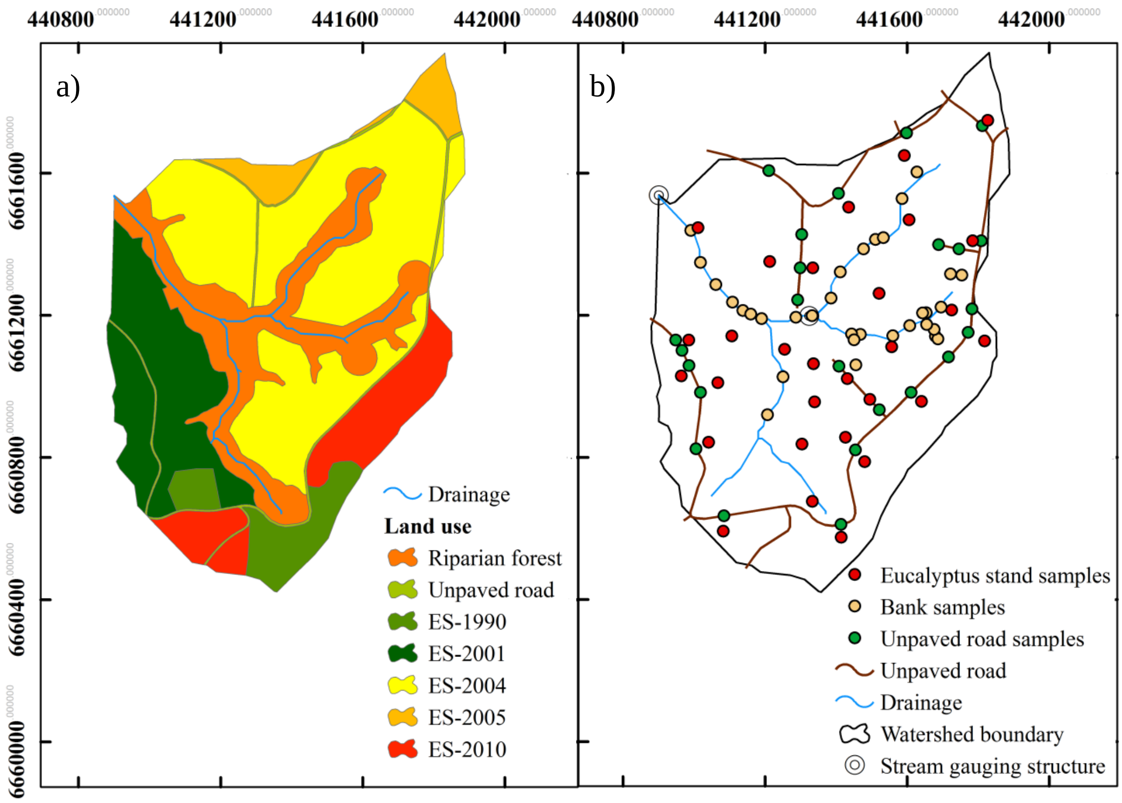

Figure 2. Land use (a) and sites sampling of potential sediment-sources (b), in Eldorado do Sul-RS, Southern Brazil.

*Eucalyptus stand (ES) planted in 1990, 2001, 2004, 2005, and 2010.

4.2.2. Source material sampling

Potential sediment sources were identified by observing sediment mobilization and transport processes operating within the watershed during and after storm events. Sampling of potential sediment-source points was concentrated in sites susceptible to erosion and potentially connectable to the stream channel. Although there was no visual evidence of erosion in eucalyptus stands, samples were collected in these areas because eucalyptus is the main land use. On the bank, exposed sites located along the main river channel network, samples were collected in two positions (Figure 3). Thus, three main sediment sources types were identified and selected (Figure 3), namely:

(i) Eucalyptus stand: samples (n = 29, for samples < 0.063 mm; n = 26, for samples > 0.063 mm)were collected in 0.00-0.05 m soil layer of eucalyptus stand, in 24 points distributed in the entire watersheds area. Each sample was composed by 6 sub-samples collected in the vicinity of the sampling point;

(ii) Bank: samples (n = 54, for samples < 0.063 mm; n = 36, for samples > 0.063 mm) were collected on bank in interface between water and air and in bank above channel water level;

(iii) Unpaved roads: samples (n = 24, for samples < 0.063 mm; n = 18, for samples > 0.063 mm) were collected in potential erosion spots observed by visual analysis, located along the unpaved roads.

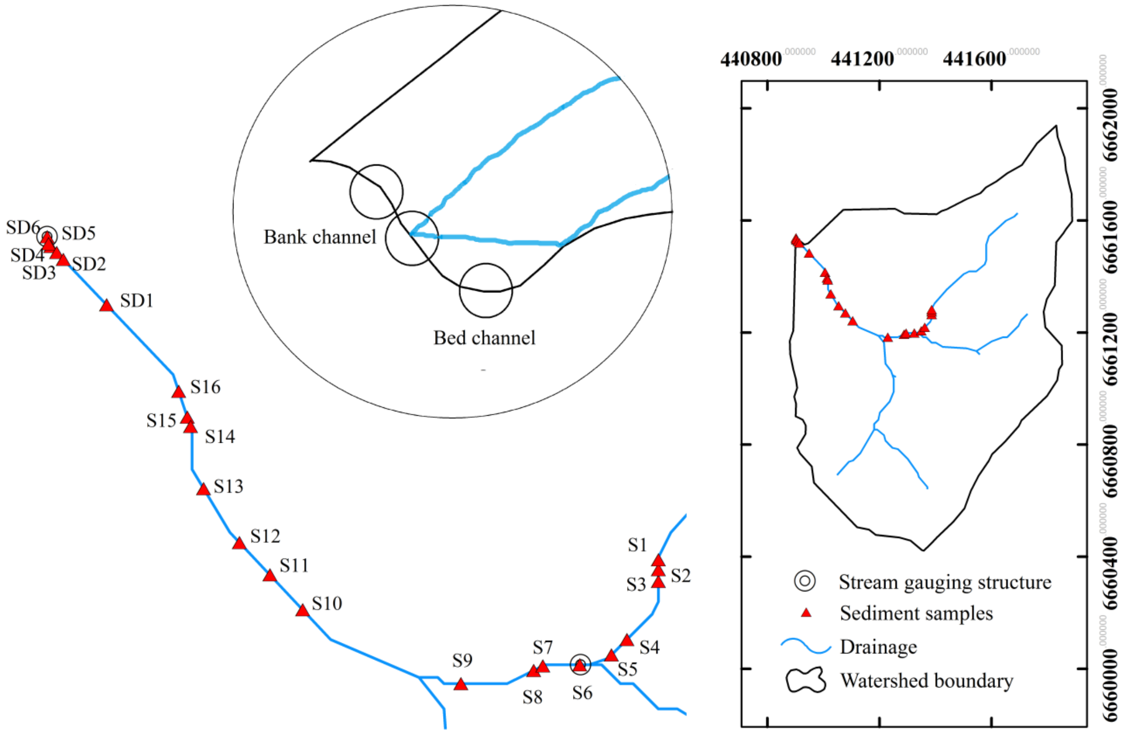

Figure 3. Sediment sites sampling.

4.2.3. Sediment sampling

Sediments used in identification analysis of sediment-producing sources were collected (i) during time intervals with a time-integrated suspended-sediments sampler, (ii) potential sediment deposition sites, near to watershed outlets, and (iii) in sites along the channel bed of the watercourse (Figure 3).

Samples of suspended sediment were collected using two time-integrated trap samplers (Phillips *et al*., 2000), installed in the monitoring section of the watershed and the sub-watershed, during two time intervals (Feb/11-Oct/11 and Nov/11-Nov/12). This sampler had a small hole that allowed the passage of flowing water. From the sedimentation principle, the material suspended in water flowing through the sampler will be accumulated in the collector bottom, composing a single sample of suspended sediment transported by water in a given period (Tiecher, 2015). These time-integration trap samplers collect fine suspended sediment (< 0.063 mm) with particle-size characteristics that are statistically representative of the suspended sediment ambient (Phillips *et al*., 2000; Tiecher, 2015).

Samples of sediment deposited in channel bed were collected in sites along the channel bed (Figure 3). Source determination at the in-stream sites was done using end member samples collected upstream of the site of interest, thus indicating how different sources dominate at different locations downstream. Locations where erosion effects were apparently higher than the deposition effects were namely sites (S_n), while locations where deposition effects were apparently higher than erosion and transport effects were namely sites of deposition (SD_n). These samples were used to determine contribution of the fine and coarse sediment.

4.2.4. Source materials and sediment analysis

Soil and sediment samples were dried at room temperature and then sieved in two size fractions: < 0.063 mm (fine), used for inductively coupled plasma mass spectrometry (ICP-MS) analysis; and 2.00-0.063 mm (coarse), used for X-Ray Fluorescence (XRF) analysis.

Samples with < 0.063 mm size were pre-treated by microwave-assisted digestion for 9.5 min at 182 ºC with concentrated HCl and HNO_3 in the ratio 3:1 (aqua regia), according to the method nº 3050B of EPA (1996). Total concentration of Al, Ba, Ca, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Na, Ni, P, Pb, Si, Sr, Ti, V, and Zn were estimated by ICP-MS.

The X-ray fluorescence (XRF) analysis was performed using samples with 0.063-2.00 mm size due the difficulty in analyzing chemical composition of coarse soil and sediments. This is an adequate analytical technique to perform elemental analysis in coarse soil and sediments because XRF combines highest accuracy and precision with simple and fast sample preparation for the non-destructive quantitative analysis of elements from Beryllium (Be) to Uranium (U), in the concentration range from 100% down to the sub-ppm-level. Thus, elements often not detected by traditional chemical analysis techniques are detectable by XRF analysis. However, XRF intensity will be influenced by soil particles size and water content in soil samples.

Soil and sediment samples were thoroughly homogenized grinded/milled and sieved into a fine, loose, powder state, with final particle sizes of < 53 μm. Since XRF spectrometers only analyze the surface layer, each sample was carefully and homogeneously prepared into pellets with smooth surfaces of equal density.

After grinding/milling and sieving procedures, ~ 2.7 g (9 pastilles) of powdery binder ("Mahlhilfe") containing cellulose was weighed into 9 g of each sample. Subsequently, 10.0 g of the mixture (sample + binding material) was homogenized, placed into deformable aluminium cups (40 mm of diameter) and compacted using a hydraulic press with a pressure of 15 Mgf during 2 minutes. Finally, the total concentration of Sc, TiO_2, V, Cr, MnO, Fe_2O_3, Co, Ni, Cu, Zn, Ga, As, Rb, Sr, Y, Zr, Nb, Mo, Sn, Sb, Cs, Ba, La, Ce, Pb, Th and U were analyzed by XRF using a GEO-QUANT T®, samples with 2.00-0.063 mm size were used for

X-Ray Fluorescence (XRF) analysis with He gas purging to allow for light elements (low proton or Z number elements) determination.

4.2.5. Statistical analysis

Sediment source identification was performed separately for fine (< 0.063 mm) and coarse sediments (0.063-2.00 mm), but the statistical methodology was the same for both sediments sizes.

Sediment source discrimination was performed by using total element concentration of source samples. Statistical analyses employed to identify composite fingerprints capable of discriminating the sources comprised two steps (Collins *et al.*, 1997): (i) test the discrimination of potential sources by the fingerprint properties, and (ii) apply a multivariate mixing model to estimate the relative contribution of the different sources to a given sediment-sample (Walling and Woodward, 1995; Walling and Collins, 2000).

4.2.5.1. Sediment source discrimination

Statistical analysis was performed to establish a set of properties able to discriminate among sediment sources, by using two sequential tests: a non-parametric Kruskal–Wallis (*H*) test and a multivariate discriminant function analysis. The *H*-test allows testing the null hypothesis that the sources are from the same population. In this test, soil properties statistically-different among sediment sources were defined and, when one soil property is statistically different, it can be used as tracer. The *H*-test was applied to each soil property, verifying its ability to discriminate individual sources (Equation 1).

$$H = \frac{12}{n(n+1)} \sum_{s-1}^{k} \frac{R_s^2}{n_1} - 3(n+1) \qquad \text{(Equation 1)}$$

where R_s is the rank sum occupied by the source s; n_1 is the number of observations in each source; n is the sum of the n_1's; and k is the number of sources.

A multivariate discriminant function analysis was performed in backward mode to determine the minimum number of properties that maximizes the discrimination among sources. This analysis was performed only with properties showing statistical differences among sources by the *H*-test. The multivariate discriminant function is based on Wilks' lambda (Λ^*) value from the analysis of variance, where the criterion used by the statistical model is the minimization of Λ^* (Johnson and Wichern, 1992) (Equation 2). Λ^* of 1 occurs if all the group are equal meaning that the sources are not different, whilst a low Λ^* value means that the variability within the groups is small compared to the total variability.

$$\Lambda^* = \frac{|W|}{|B+W|} \quad \text{(Equation 2)}$$

where |W| is the determinant of the matrix of sums of squares due to the error; and |B + W| represents the determinant of the matrix of the total sum of squares.

At each step, the property which minimized the overall Wilks' lambda was entered. Maximum significance of F to enter a property was 0.05, while minimum significance to remove a property was 0.05.

4.2.5.2. Sediment source apportionment

After defining the set of properties by minimizing Λ^*, the contribution of each sediment source in the composition of sediment was determined (Equation 3) as the mathematical relationship between the proportions of contribution of each source and geochemical properties in the sources and in the sediment (Walling and Woodward, 1995).

$$y_i = \sum_{s-1}^{n} a_{is} P_s \ (s = 1, 2, \dots, n) \ e \ (i = 1, 2, \dots, m) \quad \text{(Equation 3)}$$

where y_i is the value of the property i obtained in sediment; a_{is} are the linear model coefficients (concentration of the soil geochemical property in source s_i); and P_s is the proportion of mass from the source s, which may be presented as a set of linear functions of m properties and n sources.

To determine the P_s values an objective function was used (Walling and Woodward, 1995). The solution was found by an iterative process aiming at minimizing the value of R (f mincon) (Equation 4). The mixing model was run using Matlab® software. In the minimization process, P values are subject to two constraints: to be greater than or equal to zero and less than or equal to 1 (Equation 5), and the sum of P values must to be equal to 1 (Equation 6). The iterative process ends when the differences between modeled and measured chemical concentrations in sediment are minimized.

$$R = \sum_{i=1}^{m} \left\{ \frac{\left(C_i - \left(\sum_{s=1}^{n} P_s C_{si}\right)\right)}{C_i} \right\}^2 \qquad \text{(Equation 4)}$$

$$0 \leq P_s \leq 1 \qquad \text{(Equation 5)}$$

$$\sum_{s=1}^{g} P_s = 1 \qquad \text{(Equation 6)}$$

where m is the number of soil properties selected as properties tracer; n is the number of sources; C_i is the concentration of the tracer i in the suspended sediment sample; P_s is the proportion of contribution of the source s (unknown property that the model estimates by iteration); and C_{si} is the average value of the tracer i obtained at the source s.

The optimization process (Equation 4) was checked whether it provided acceptable results of the relative contribution from the sediment sources. The evaluation of the results was made by comparing the concentration of geochemical property used (properties tracers) in the sediment and the value predicted by the model based on the proportion calculated for each source. Then, with the values of relative error of each geochemical property, a mean (RME) was calculated to provide a unique value associated with each sample of suspended sediment (Equation 7). When the result of RME is less than 15% it indicates the model found a feasible solution of P_s values (relative contributions of each source) from the minimization procedure (Equation 4) (Walling and Collins, 2000).

$$ERM = \sum_{i=1}^{m} \left\{ \frac{C_i - \left(\sum_{s=1}^{n} P_s \, C_{si}\right)}{m} \right\} \qquad \text{(Equação 7)}$$

4.3. Results and discussion

4.3.1 Sediment source discrimination

4.3.1.1 Kruskal-Wallis test (*H*)

For fine sediments, from the twenty geochemical properties analyzed, sixteen (Al, Ca, Co, Cr, Fe, K, Li, Mg, Na, Ni, P, Pb, Sr, Ti, V, and Zn) were selected as a potential tracers for fine sediment by applying Kruskal-Wallis test, whilst four of them were not selected (Ba, Cu, Mn e Si) (Table 1). Discriminant function analysis showed the discriminatory power of individual properties ranged from 59.8 to 88.8%, where no single property was able to correctly classify 100% of the source samples in their respectively groups (Table 1). These sixteen geochemical properties were considered as tracer property identified by the Kruskal-Wallis test as providing statistically significant discrimination between at least two sediment-sources and were then entered into the stepwise multivariate discriminant function analysis, in order to select the optimum set for maximizing discrimination, whilst minimizing dimensionality.

Table 1. Kruskal-Wallis (*H*) test output for geochemical properties in fine sediments.

Property	Kruskal-Wallis test		% source samples classified correctly	Eucalyptus stand	Bank	Unpaved road
	H	*p*-value*		M±SD**	M±SD	M±SD
Al ($\mu g\ g^{-1}$)	43.9	< **0.001**	59.8	53971.0±24549.2	52789.7±17596.6	106351.9±22776.3
Ba ($\mu g\ g^{-1}$)	5.0	0.080	64.5	145.3±54.2	128.7±62.5	116.8±59.1
Ca ($\mu g\ g^{-1}$)	17.6	< **0.001**	-	1481.3±1448.0	1212.2±1251.5	548.5±502.7
Co ($\mu g\ g^{-1}$)	23.0	< **0.001**	68.2	7.5±4.0	11.5±6.2	7.7±5.3
Cr ($\mu g\ g^{-1}$)	19.9	< **0.001**	73.8	22.9±11.5	37.2±19.2	48.3±28.6
Cu ($\mu g\ g^{-1}$)	5.1	0.080	-	16.1±7.2	21.3±12.1	21.4±9.4
Fe ($\mu g\ g^{-1}$)	22.1	< **0.001**	75.7	26529.9±11203.4	28236.6±19582.5	41998.9±12752.9
K ($\mu g\ g^{-1}$)	7.6	**0.020**	88.8	3968.5±2173.7	4924.0±2584.8	5952.4±3330.0
Li ($\mu g\ g^{-1}$)	27.0	< **0.001**	83.2	15.1±4.8	24.3±10.6	23.0±11.5
Mg ($\mu g\ g^{-1}$)	32.4	< **0.001**	86.0	1544.6±540.8	3126.7±2420.3	2232.9±1719.4
Mn ($\mu g\ g^{-1}$)	2.6	0.270	-	531.8±338.9	431.2±292.7	388.5±210.0
Na ($\mu g\ g^{-1}$)	6.0	**0.050**	88.8	143.5±42.2	181.5±76.5	172.9±61.8
Ni ($\mu g\ g^{-1}$)	20.6	< **0.001**	83.2	7.9±3.8	14.0±9.1	14.2±11.6
P ($\mu g\ g^{-1}$)	8.0	**0.020**	88.8	381.7±174.8	303.0±249.1	264.5±117.0
Pb ($\mu g\ g^{-1}$)	13.3	< **0.001**	79.4	10.1±11.3	19.0±11.9	16.4±11.5
Si ($\mu g\ g^{-1}$)	2.8	0.240	-	1692.4±595.9	1641.1±1098.8	1726.6±1230.5
Sr ($\mu g\ g^{-1}$)	12.9	< **0.001**	86.0	21.9±16.0	17.2±11.2	11.2±6.5
Ti ($\mu g\ g^{-1}$)	15.8	< **0.001**	88.8	1241.4±359.6	1053.1±268.6	826.1±369.8
V ($\mu g\ g^{-1}$)	14.1	< **0.001**	86.9	56.4±21.2	60.4±22.1	81.5±26.7
Zn ($\mu g\ g^{-1}$)	8.7	**0.010**	87.9	51.0±21.2	68.3±31.1	61.5±25.2

*Bold p values indicate significant differences among the sediment sources at $p < 0.05$.

**M: mean; SD: Standard deviation.

For coarse sediment, from the twenty-seven geochemical properties analyzed, nineteen (As, Ba, Ce, Co, Cu, Fe_2O_3, Ga, La, MnO, Pb, Rb, Sb, Sc, Sr, Th, V, Y, Zn, and Zr) were selected as a potential tracers by applying Kruskal-Wallis test, whilst ten of them were not selected (Co, Cr, Cs, Cu, Mo, Nb, Ni, Sn, TiO_2, and U) (Table 2). Discriminant function analysis shows the discriminatory power of individual properties ranged from 49.4 to 82.3%, where no single property was able to correctly classify 100% of the source samples in their respectively groups (Table 2). These geochemical properties (19) were considered as tracer property identified by the Kruskal-Wallis test.

Table 2. Kruskal-Wallis (*H*) test output for geochemical properties in coarse sediments.

Property	Kruskal-Wallis test		% source samples classified correctly	Eucalyptus stand	Bank	Unpaved road
	H	*p*-value*		M±SD**	M±SD	M±SD
As (ppm)	11.7	**0.003**	82.3	16.2±3.6	13.9±1.6	16.4±3.2
Ba (ppm)	43.1	< **0.001**	81.0	257.0±110.7	501.8±82.3	244.3±185.5
Ce (ppm)	22.4	< **0.001**	79.7	55.3±20.5	102.0±44.6	92.7±39.9
Co (ppm)	1.5	0.476	-	14.9±7.6	17.5±9.8	17.4±6.3
Cr (ppm)	2.8	0.249	-	1854.7±1137.2	1678.0±1461.6	2091.2±1088.4
Cs (ppm)	3.0	0.228	-	8.0±3.2	8.3±2.4	9.8±3.8
Cu (ppm)	1.3	0.532	-	44.1±21.2	48.2±31.2	49.9±21.6
Fe_2O_3 (%)	10.8	**0.005**	81.0	3.9±1.3	4.1±2.2	5.4±1.5
Ga (ppm)	21.2	< **0.001**	49.4	10.8±3.9	14.6±5.7	18.6±5.8
La (ppm)	29.9	< **0.001**	81.0	18.4±11.6	51.2±26.8	35.0±22.9
MnO (%)	5.9	**0.053**	81.0	0.08±0.05	0.06±0.03	0.05±0.02
Mo (ppm)	2.5	0.282	-	14.3±8.8	13.6±12.8	16.1±8.2
Nb (ppm)	0.6	0.737	-	18.9±8.4	16.7±4.0	16.4±4.3
Ni (ppm)	2.3	0.310	-	729.2±483.0	714.6±675.8	826.1±444.8
Pb (ppm)	8.5	**0.014**	79.7	23.8±13.1	32.7±24.3	23.8±6.9
Rb (ppm)	27.3	< **0.001**	73.4	76.3±37.8	133.2±30.7	100.4±54.9
Sb (ppm)	9.1	**0.010**	78.5	1.9±1.1	1.1±1.1	1.2±0.9
Sc (ppm)	10.3	**0.006**	82.3	7.2±3.4	8.9±3.9	10.7±3.4
Sn (ppm)	0.3	0.852	-	5.5±2.5	12.9±35.7	4.9±2.7
Sr (ppm)	41.6	< **0.001**	74.7	34.3±17.0	69.5±22.3	27.5±22.8
Th (ppm)	18.5	< **0.001**	78.5	6.0±3.9	10.9±7.2	12.9±6.8
TiO_2 (%)	0.2	0.887	-	0.8±0.4	0.8±0.2	0.7±0.2
U (ppm)	5.8	0.054	81.0	2.5±2.0	3.5±1.9	2.8±1.2
V (ppm)	8.3	**0.016**	78.5	56.5±13.6	59.3±17.4	74.4±22.3
Y (ppm)	21.0	< **0.001**	77.2	18.2±5.3	26.9±9.2	20.8±6.0
Zn (ppm)	12.9	**0.002**	82.3	33.7±19.5	49.8±26.6	37.6±17.9
Zr (ppm)	6.5	**0.038**	78.5	349.0±112.2	391.0±134.1	314.7±111.6

*Bold p values indicate significant differences among the sediment sources at $p < 0.05$.

**M: mean; SD: Standard deviation.

4.3.1.2 Discriminant function analysis

Introduction of the properties into the analysis provided progressive reduction in Wilks' lambda value (Λ*). The set of properties selected for fine sediments by general discriminant function analysis comprised seven properties (elements), namely Al, Li, Pb, Ti, Sr, Cr and V (Table 3). The final value of the Λ* parameter was 0.1674. As the value of Λ* is the proportion of total variance due to the error of source discrimination, the selected properties provided an error of approximately 16.7%, which means the set of selected properties explains approximately 83.3% of the difference among sources. Consequently, some samples were no correctly classified in their respective sediment-source. For fine sediments the correct classification for each sediment-source was 79.3% for eucalyptus stand, 90.7% for bank, and 87.5% for unpaved road, which provides 86.9% of the total correct classification (Table 4).

For coarse sediments, the set of properties selected by general discriminant function analysis comprised five properties, namely Ba, V, MnO, La and Th (Table 3). The final value of the Λ^* parameter was 0.2431; consequently, selected properties provided an error of approximately 24.3%; thus the set of selected properties explains approximately 75.7% of the difference among sources. As observed for fine sediments, some samples were not classified correctly where for coarse sediments the correct classification was 76.9% for eucalyptus stand, 91.4% for bank, and 66.7% for unpaved road, which provides 81.0% of the total correct classification (Table 4).

Correct classification of samples in their respective sediment-source may be variable, as observed by Tiecher *et al*. (2014; 2015a,b) and Minella *et al*. (2008), and depends of the number of properties to represent geomorphologic and anthropic processes (Tiecher *et al*., 2014) capacity of set properties indicate de differences among sediment-sources. Tiecher *et al*. (2014; 2015a,b) found 100%, whilst Minella *et al*. (2008) 92.9% of source type samples classified correctly, which shows higher potential of the selected properties in their studies to explain the differences among sources than properties selected in our study.

Sediment-sources were separated by a significant Mahalanobis distance of 7.3±2.1 for fine sediments and 5.0±1.5 for coarse sediments from each other sediment-sources (Table 4 and Figure 4). Mahalanobis distance shows the unpaved road and bank sediment-sources are the most similar in terms of their fingerprinting properties; eucalyptus stand are closer to bank, and further to unpaved road sediment-sources for fine sediments. However, for coarse sediments, the eucalyptus stand and bank sediment-sources are the most similar; eucalyptus stand are closer to unpaved road, and bank are further to unpaved road sediment-sources (Table 4 and Figure 4). Even that the distances among all sources were significantly different the scatter of points within each group introduces a source of uncertainty; when a sample is classified correctly, it is important to consider the distance to the group central point (Figure 4). We calculated the uncertainty associated to each source as suggested by Minella *et al*.

(2008) and Tiecher *et al*. (2015a) considering: (i) the distance between the groups, (ii) the percent of samples incorrectly classified, and (iii) the scatter within the group.

Table 3. Results of the stepwise discriminant function analysis as indicated by the Wilks' lambda values for geochemical properties of fine and coarse sediments.

Step	Property selected	Wilk's lambda	*p* to remove	Cumulative % of source type samples classified correctly
		Fine sediments		
1	Al	0.4616	0.0000000	59.8
2	Li	0.3376	0.0000001	82.2
3	Pb	0.3075	0.0000015	82.2
4	Ti	0.2565	0.0000142	80.4
5	Sr	0.2055	0.0000294	85.0
6	Cr	0.1921	0.0006585	84.1
7	V	0.1674	0.0011639	86.9
		Coarse sediments		
1	Ba	0.4792	0.000000	65.8
2	V	0.4151	0.000175	74.7
3	MnO	0.3266	0.000250	78.5
4	La	0.2676	0.003113	82.3
5	Th	0.2431	0.005911	78.5

Table 4. Discriminant analysis output and prediction error of fingerprinting approach for fine and coarse sediments.

Discriminant function analysis parameters	Fine sediments	Coarse sediments
Discriminant function analysis output		
Wilks' lambda	0.1674	0.2431
Variance due to differences among sources (%)	83.3	75.7
Degree of freedom	14;196	10;144
$F_{calculated}$	20.22	14.81
$F_{critical}$	2.98	2.72
p-value	< 0.0000	< 0.0000
F-values		
Degree of freedom	7;98	5;72
$F_{critical}$	7.24	3.63
Eucalyptus stand *vs*. Bank	13.8	25.0
Eucalyptus stand *vs*. Unpaved road	22.5	6.6
Bank *vs*. Unpaved road	27.8	15.5
p-levels		
Eucalyptus stand *vs*. Bank	0.000000	0.000000
Eucalyptus stand vs. Unpaved road	0.000000	0.000041
Bank *vs*. Unpaved road	0.000000	0.000000

Squared Mahalanobis distances		
Eucalyptus stand *vs*. Bank	6.6	3.8
Eucalyptus stand *vs*. Unpaved road	9.7	4.6
Bank *vs*. Unpaved road	5.6	6.8
Average	7.3	5.0
Source type classified correctly		
Eucalyptus stand	79.3	76.9
Bank	90.7	91.4
Unpaved road	87.5	66.7
Uncertainty associated with the discrimination of the source (%)		
Eucalyptus stand	26.6	29.3
Bank	14.6	13.6
Unpaved road	18.2	37.3
Average	19.8	26.7

The uncertainty associated with the discrimination of each sediment-source was 26.6% for eucalyptus stand, 14.6% for bank, and 18.2% for unpaved road for fine sediments; whilst for coarse sediment uncertainty was higher than for fine sediment for eucalyptus stand (29.3% and for unpaved road (37.3%) (Table 4). These uncertainty associated with the discrimination of each sediment-source was higher than values observed by Minella *et al*. (2008) and Tiecher *et al*. (2015a), which explain the importance of to associate approaches for improve the discrimination capacity.

Scatterplot of canonical scores shows the relationship between sets of properties finding a small number of linear combinations, for each set of properties, to maximize the possible correlation among sources (Figure 4). Discrimination of the three sediment-sources for fine and for coarse sediments was clearly provided by the geochemical properties.

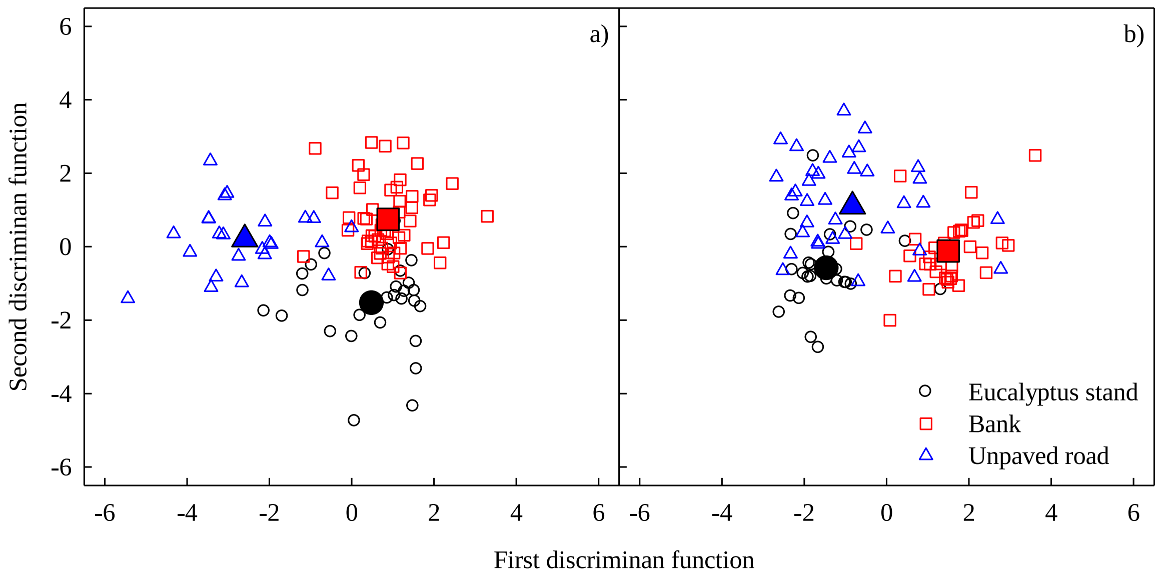

Figure 4. Scatterplot of canonical scores of the first and second discriminant functions from stepwise discriminant function analysis for geochemical properties of fine (a) and of coarse sediments (b). Larger symbols represent the centroids of each source.

4.3.2 Source apportionment

The model of sediment-sources classification was efficient to determine source contribution of fine sediments, because the relative error was less than 15% for most sediment samples (Table 5), and was low efficient to determine the source contribution of coarse sediments, where relative error was higher than 15% for some sediment samples (Table 5). A relative error of less than 15% indicates that the model algorithm is able to provide an acceptable prediction of the fingerprint property concentrations associated with the deposited sediment samples (Walling and Collins, 2000) for the sites in the watershed. Even though errors were greater than 15% for identification of coarse-sediment source, the results were presented and explored, given the evidence of the sources through visual analysis in the watershed.

Table 5. Relative contribution of sediment source groups to the sediment of individual sampled sites.

Sediment site	Area (km^{-2})	Fine sediment				Coarse sediment			
		Relative sediment source contribution (%)			RME (%)	Relative sediment source contribution (%)			RME (%)
		Eucalyptus stand	Bank	Unpaved road		Eucalyptus stand	Bank	Unpaved road	
S1	0.205	0.0	92.9	7.1	6.0	15.2	84.8	0.0	12.7
S2	0.207	0.0	73.4	26.6	16.4	33.0	33.0	34.0	0.0

S3	0.207	0.0	93.2	6.8	6.7	-	-	-	-
S4	0.220	0.0	94.2	5.8	5.2	-	-	-	-
S5	0.221	0.0	89.5	10.6	12.4	67.9	32.1	0.0	> 15
S6	0.393	0.0	88.9	11.1	6.0	0.0	38.6	61.4	> 15
S7	0.396	0.0	100.0	0.0	5.1	-	-	-	-
S8	0.397	0.0	99.8	0.2	4.7	26.5	73.5	0.0	15.7
S9	0.407	0.0	100.0	0.0	5.1	-	-	-	-
S10	0.807	0.0	100.0	0.0	1.5	-	-	-	-
S11	0.850	0.0	100.0	0.0	4.6	100.0	0.0	0.0	> 15
S12	0.850	0.0	100.0	0.0	4.0	33.0	33.0	34.0	0.0
S13	0.890	0.0	100.0	0.0	10.9	69.5	30.5	0.0	> 15
S14	0.909	0.0	81.9	18.1	8.4	100.0	0.0	0.0	> 15
S15	0.909	0.0	100.0	0.0	3.0	-	-	-	-
S16	0.915	0.0	100.0	0.0	3.0	-	-	-	-
SD1	0.962	6.9	81.5	11.5	3.2	7.5	92.5	0.0	2.0
SD2	0.962	12.6	77.3	10.1	2.3	0.0	79.4	20.6	4.3
SD3	0.962	0.0	93.2	6.8	1.5	0.0	95.3	4.7	1.0
SD4	0.967	0.0	82.1	17.9	1.0	15.1	53.9	31.1	5.9
SD5	0.967	29.0	53.9	17.1	1.7	0.0	58.5	41.5	6.9
SD6	0.977	0.0	30.1	69.9	1.6	0.0	0.0	100.0	> 15

*RME: relative mean error (%).

For fine sediment, the contribution of sediment sources (RME < 15.0%) was different according to drainage area for each sediment deposit site (Figure 5). However, in general, main source of fine-sediment was the bank (Figure 5 and Table 5). Calculated mean relative contribution of each sediment-source to sediment deposition for sites with lower drainage area or close to unpaved roads indicated unpaved roads also contributed to fine-sediment deposit, probably due the higher proportion of this land use in smaller watersheds and the proximity of this source with the drainage network. Similar results were observed by Tiecher (2015), where unpaved roads provided more contribution of sediment yield for smaller watersheds. Generally, by increasing the drainage area the main sediment-source also was the bank. However, for sites closer to the watershed outlet, where the contribution areas are greater and the land slope is lower than for smaller drainage areas, eucalyptus stand and unpaved road also contributed for sediment generation. Less steep relief of these sites and the blockage effect by the weir installed in the watershed outlet help to accumulate discharge flow (Rodrigues *et al.*, 2014); consequently, the energy for sediment transport reduces and deposition of sediment from distant sources occurs.

The main source of coarse-sediment (RME < 15.0%) was the bank (Figure 5 and Table 5) for sites with lower drainage area and for sites with greater drainage area located close to the watershed outlet, but unpaved roads and eucalyptus stand also contributed to sediment generation.

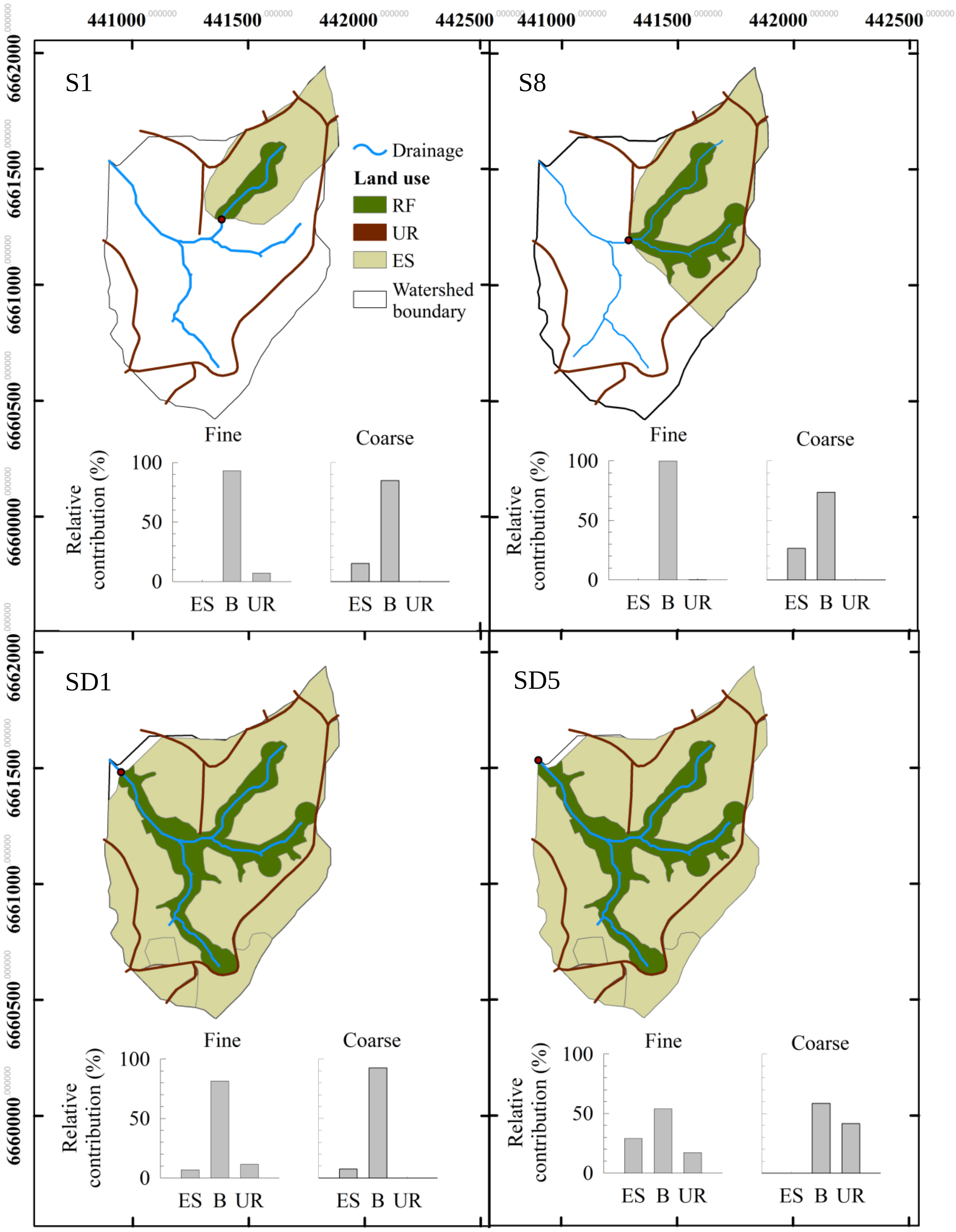

Figure 5. Relative contribution of fine and coarse-sediment-source to sediment deposited in sites (S1, S8, SD1, SD5) with different drainage area. RF: riparian fores; ES: eucalyptus stand; B: bank; UR: unpaved road.

Eucalyptus stand showed lower contribution than the unpaved roads and bank, because of the limited erosion and disaggregation of surface soil. Unpaved roads show low contribution, possibly due the small area of this land use and due to reduced need for maintenance, and because there was no construction of new roads for most study period. The low contribution of eucalyptus stands to fine and coarse sediment yield shows the effectiveness of surface litter and canopy protection (Mizugaki *et al*., 2008), runoff control (Mello *et al*., 2007) and, consequently, erosion control in areas cropped to eucalyptus. Despite the low sediment contribution from eucalyptus stands and watercourse bank protection by riparian vegetation, high contribution of banks for sediment yield highlights the fragility of the soils, independent of the riparian vegetation land use area or the type of riparian vegetation.

Watercourse bank mass failure resulted from fluvial erosion at the toe of the bank with continuous removal of bank material, causing changes in bank slope by over-deepening the bank and altering bank angle. Additionally to forces of running water, surcharge from the weight of trees accelerates the erosion process (Rauch *et al*., 2014). Surcharge and near-surface moisture are destabilization effects that affect slope stability (Rauch *et al*., 2014; Simon and Collison, 2002). Contribution of banks may be provided by gravity associated with effects from variations in temperature and wetness, especially when rainfall events occur, which may result in undermining and collapse due to slope instability. This instability occurs when shear stress of flowing water is greater than soil shear strength.

Instability of the bank results from a continuous process of erosion, landslide and collapse. This instability prevents vegetation from spontaneous establishment. Additionally, the riparian forest did not provide bank stabilization, because taller trees provided an overhead in the vertical axes, shifting its center of gravity in a less stable position. They transmit wind power to the slope, probably amplifying the dynamics of landslides, initially triggered by stream flow (Durlo and Sutili, 2005).

Bank mass failure provides sediment accumulation on channel bed, and the distance that these sediments will be transported depends on particle sizes and streamflow energy for transport. Thus, the difference in sediment-sources contribution along the stream network occurs due to the contribution of each source and due to the energy required for transport of particles with different sizes. During rainfall events, energy of streamflow transports coarse sediments to closer areas downstream where they remain deposited until the next rainfall event. In contrast, fine sediments are transported to more distant areas, with the same transport energy.

An important sediment source for small watersheds is sediment deposited into the channel (Rodrigues *et al*., 2014), as observed in our results of relative contribution of each sediment-source for sediment deposition sites. Rodrigues *et al*. (2014) observed the predominant direction of hysteresis loops was clockwise, which suggest proximity of the sediment-sources location (Eder *et al*., 2010; Seeger *et al*., 2004). Similarly to our results, Schuller *et al*. (2013) conducted sediment source fingerprinting investigation in small forest watersheds where the long-term mean annual rainfall is 1,200 mm, similar to our condition, and they observed during the period prior to clear-cutting that the dominant sediment-source was the stream channel (47%), with 37% contributed by the roads and only 16% from the watershed slopes. Minella et al. (2009a) evaluated sediment-source before and after the introduction of conservation tillage practices in a small (1.19 km^2) rural watershed. They observed significant reductions in storm runoff, maximum flow rate and sediment yield after implementation of the conservation practices, and, consequently, a statistically significant reduction in the proportion of the sediment contributed by fields (62% to 54%) and unpaved roads (36% to 24%). This reduction was offset by an increased contribution of sediment from channel sources (2% to 22%). They attributed that increase proportion of sediment mobilized from the channel is in part a function of the reduced contribution from the two other sources, but it also reflects the reduction in sediment inputs to the channel from the fields and unpaved roads, which results in an increase in the energy available for channel scour.

Investigation of longitudinal changes in sediment source contributions was also an important part of the study made by Palazón *et al*. (2015), while Haddadchi *et al*. (2015) found that proximal sources tended to contribute more to a given river sampling point than more distal sources, in a nested watershed study based on geological source areas. Minella *et al*. (2014) observed the budget calculations indicate that rural small watershed had a sediment delivery ratio of ∼15%, whilst in our watershed study a sediment delivery ratio was 0.71% (Rodrigues, 2011). Change in the contribution of sediment-sources along with the stream network were attributed to variations in land use, erosion processes, and sediment storage that reduces the proportion of upstream sediments reaching a given measurement site (Smith *et al*., 2015).

The classification model for sediment-sources was efficient to determine source contribution of fine sediments, because the results indicate the bank as the main sediment-source which is consistent with the observed field experience; and because the relative error was less than 15% for all fine sediment and for most coarse sediment samples (Figure 6).

Fine-sediment source contribution for sediments collected from the monitoring sections was different for the watershed and sub-watershed (Figure 6).

During the first time period(Feb/11-Oct/11), the main sediment-source for the watershed and the sub-watershed was the bank (92.19% and 92.91%, respectively) and the unpaved road provided lower contribution (7.81% and 7.09%, respectively) (Figure 6), whilst eucalyptus stand does not contributed to sediment generation. For second time period (Nov/11-Nov/12), all three sources contributed, where the main source was bank for the watershed and for the sub-watershed (74.41% and 91.24%, respectively). Eucalyptus stand was a source only for this evaluation and contributed with 15.68% for the watershed and 7.78% for the sub-watershed. Unpaved road provided lower contribution to sediment generation than others sediment-sources (9.91% and 0.98%, respectively) during the second time period.

The main contribution of the streamflow sites are in consonance with soil fragility on the banks. Eucalyptus stand had lower contribution than the main sediment-source, probably because of the protecting effect of surface litter and canopy (Mizugaki *et al*., 2008) and runoff control (Mello *et al*., 2007). Despite this soil protection, eucalyptus stand shows contribution to sediment yield during the second period, probably due the rainfall characteristics during this time. Total rainfall volume was similar during the two time periods (Feb/11-Oct/11: 1247 mm; Nov/11-Nov/12: 1409 mm), however during the second period one rainfall event (266 mm) provided sediment yield of 51.7 Mg km^{-2} for the watershed and 99.8 Mg km^{-2} for the sub-watershed. This event probably provided high runoff and soil erosion in all land uses in the watershed and sub-watershed, thus the identification of sediment-sources and the magnitude of sediment yield during rainfall–runoff events are of great importance (Rodrigues *et al*., 2014). Similar behavior was also observed by Tiecher *et al*. (2014), where the main sediment-source was unpaved road in periods with expected rainfall periods according to long-term climate average; however, the main sediment-source change to field crops when the extreme rainfall events (about four times higher than long-term average) occurred.

The contribution of sediment-sources predicted by conventional approach based on geochemical composition shows that sediment-source contributions vary from one rainfall event to another, as also observed by (Tiecher *et al*., 2015b). This result shows the fingerprinting approach is sensitive to evaluate sediment-sources during extreme or with high magnitude rainfall events.

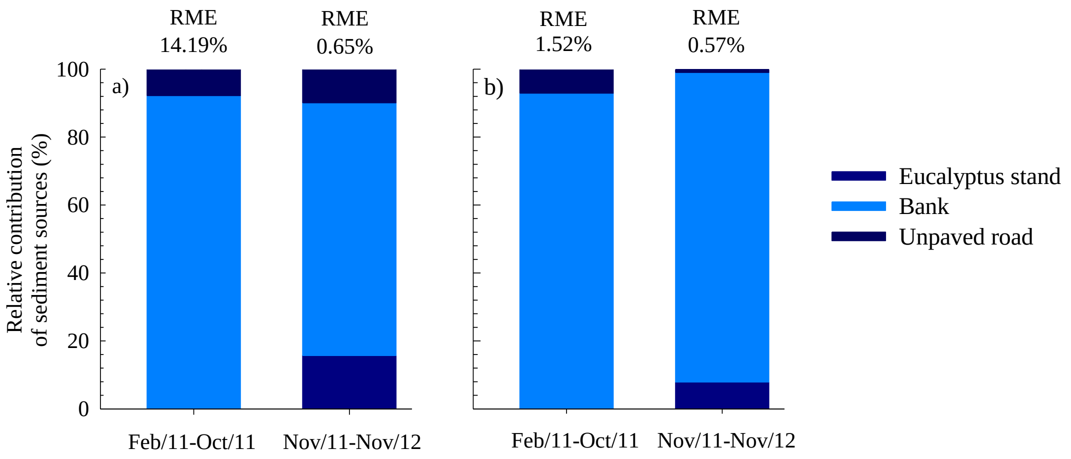

Figure 6. Distribution of the relative contributions from three sediment-sources collected in two time periods in the watershed monitoring section (a) and in the sub-watershed monitoring section (b).

4.4. Conclusions

Sediment source apportionment results demonstrate that source contributions vary both with particle size and location within the watershed. We used geochemical properties to evaluate both fine and coarse sediments. However, the model of sediment-sources classification had low efficient to determine source contribution of coarse sediments. These results show that complex dynamics of erosion imply the identification of sediment-sources and techniques types need improvement. An alternative is to combine both environmental and statistical approaches to tracer selection, as visible-based-color parameters to improve sediment-source identification.

The closer the source is to stream, the higher is its contribution. For all size fractions, proximal sediment-sources are more likely to have a greater contribution to suspended sediments in the watershed. However, more study time is necessary to support this initiatory evidence.

The major sediment contribution is from stream network, especially bank. This indicates that management actions should be focused on the more proximal sources instead of eucalyptus stands. Soil bioengineering techniques, composed of physical actions and implementation of vegetation, are thus an option to protect the stream network in the watershed.

There are other factors which may affect the predominance of sediment sources and need further assessment, including slope, variation of volume and intensity of rainfall, change in land use, and, especially in our study area, changes in the relative contribution of sediment-sources of different sediment-sizes caused by forestry operations. Attention should be focused on post-harvest periods and post-replanting period, which were not evaluated in our study.

4.5. References

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G. 2013. Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift* **22**:711-728.

Bai X, Zhang X, Long Y, Liu X, Siyu Z. 2013. Use of ^{137}Cs and $^{210}Pb_{ex}$ measurements on deposits in a karst depression to study the erosional response of a small karst catchment in Southwest China to land-use change. *Hydrological Processes* **27**:822-829.

Bergamaschi H, Guadagnin MR, Cardoso LS, Silva MIG. 2003. Clima da Estação Experimental da UFRGS (e região de abrangência). Porto Alegre: UFRGS. 77p.

Bergamaschi H, Melo RW, Guadagnin MR, Cardoso LS, Silva MIG, Comiran F, Dalsin F, Tessari ML, Brauner PC. 2013. *Boletins agrometeorológicos da Estação Experimental Agronômica da UFRGS: Série histórica 1970-2012*. Porto Alegre: UFRGS.

Bilotta GS, Brazier RE. 2008. Understanding the influence of suspended solids on water quality and aquatic biota. *Water Resources* **42**:2849-2861.

Blake WH, Ficken KJ, Taylor P, Russell MA, Walling DE. 2012. Tracing crop-specific sediment sources in agricultural catchments. *Geomorphology* **139-140**:322-329.

Bonumá NB, Rossi CG, Arnold JG, Reichert JM, Minella JPG, Allen PM, Volk M. 2013. Simulating landscape sediment transport capacity by using a modified SWAT Model. *Journal of Environmental Quality* **43**:55-66.

Caitcheon GG, Olley JM, Pantus F, Hancock G, Leslie C. 2012. The dominant erosion processes supplying fine sediment to three major rivers in tropical Australia, the Daly (NT), Mitchell (Qld) and Flinders (Qld) Rivers. *Geomorphology* **151-152**:188-195.

Collins AL, Walling DE, Leeks GJL. 1997. Source type ascription for fluvial suspended sediment based on a quantitative composite fingerprinting technique. *Catena* **29**:1-27.

Collins AL, Zhang Y, Walling DE, Grenfell SE, Smith P. 2010. Tracing sediment loss from eroding farm tracks using a geochemical fingerprinting procedure combining local and genetic algorithm optimisation. *Science of the Total Environment* **408**:5461-5471.

Collins AL, Zhang Y, Walling DE, Grenfell SE, Smith P, Grischeff J, Locke A, Sweetapple A, Brogden D. 2012. Quantifying finegrained sediment sources in the River Axe catchment, southwest England: application of a Monte Carlo numerical modelling framework incorporating local and genetic algorithm optimisation. *Hydrological Processes* **26**:1962-1983.

Costa AM, Curi N, Menezes MD, Araújo EF, Marques JJ. 2009. Levantamento detalhado de solos da microbacia hidrográfica do horto florestal Terra Dura (RS) e considerações sobre escalas de mapeamento. *Ciência & Agrotecnologia* **33**: 1272-1279.

D'Haen K, Verstraeten G, Degryse P. 2012. Fingerprinting historical fluvial sediment fluxes. *Progress in Physical Geography* **36**:154-186.

Devereux OH, Prestegaard KL, Needelman BA, Gellis AC. 2010. Suspended-sediment sources in an urban watershed, Northeast Branch Anacostia River, Maryland. *Hydrological Processes* **24**:1391-1403.

Durlo MA, Sutili FJ. 2005. *Bioengenharia: Manejo biotécnico de cursos de água*. Porto Alegre: EST Edições, 198.

Eder A, Strauss P, Krueger T, Quinton JN. 2010. Comparative calculation of suspended sediment loads with respect to hysteresis effects (in the Petzenkirchen catchment, Austria). *Journal of Hydrology* **389**:168-176.

EMBRAPA. 2006. *Sistema Brasileiro de Classificação de Solos*. 2.ed. Brasília: Embrapa. 306p.

EPA - Environmental Protection Agency. 1996. Method 3050B. *Acid digestion of sedments, sludges, and soils*.

USDA - United States Department of Agriculture. 1999. Soil Survey Staff. *Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys*. 2nd ed. U.S. Department of Agriculture/Natural Resources Conservations Service, Washington, Agriculture Handbook. 871pp.

Evrard O, Navratil O, Ayrault S, Ahmadi M, Némery J, Legout C, Lefèvre I, Poirel A, Bonté P, Esteves M. 2011. Combining suspended sediment monitoring and fingerprinting to determine the spatial origin of fine sediment in a mountainous river catchment. *Earth Surface Processes and Landforms* **36**:1072-1089.

Evrard O, Poulenard J, Némery J, Ayrault S, Gratiot N, Duvert C, Prat C, Lefèvre I, Bonté P, Esteves M. 2013. Tracing sediment sources in a tropical highland catchment of central Mexico by using conventional and alternative fingerprinting methods. *Hydrological Processes* **27**:911-922.

Foster IDL, Boardman J, Keay-Bright J. 2007. Sediment tracing and environmental history for two catchments, Karoo Uplands, South Africa. *Geomorphology* **90**:126-143.

Fox JF, Papanicolaou AN. 2007. The use of carbon and nitrogen isotopes to study watershed erosion processes. *Journal of the American Water Resources Association* **43**:1047-1064.

Franz C, Makeschin F, Wei H, Lorz C, 2014. Sediments in urban river basins: identification of sediment sources within the Lago Paranoá catchment, Brasilia DF, Brazil - using the fingerprint. *Science of The Total Environment* **466-467**:513-523.

Fukuyama T, Onda Y, Gomi T, Yamamoto K, Kondo N, Miyata S, Kosugi KI, Mizugaki S, Tsubonuma N. 2010. Quantifying the impact of forest management practice on the runoff of the surfacederived suspended sediment using fallout radionuclides. *Hydrological Processes* **24**:596-607.

Haddadchi A, Olley J, Pietsch T. 2015. Quantifying sources of suspended sediment in three size fractions. *Journal of Soils and Sediments* **15**:2086-2100.

Johnson RA, Wichern DW. 1992. *Applied multivariate statistical analysis*. London, Prentice-Hall International. 642p.

Koiter AJ, Owens PN, Petticrew EL, Lobb DA. 2013. The behavioural characteristics of sediment properties and their implications for sediment fingerprinting as an approach for identifying sediment sources in river basins. *Earth Science Reviews* **125**:24-42.

Lima WP. 1990. Overland flow and soil and nutrient losses from Eucalyptus plantations. *IPEF International* **1**:35-44.

Lombardi Neto F, Moldenhauer WC. 1992. Erosividade da chuva: sua distribuição e relação com as perdas de solo em Campinas (SP). *Bragantia* **51**:189-196.

Mello CR, Lima JM, Silva AM. 2007. Simulação do deflúvio e vazão de pico em microbacia hidrográfica com escoamento efêmero. *Revista Brasileira de Engenharia Agrícola e Ambiental* 11:410-419.

Miguel P, Dalmolin RSD, Pedron FA, Moura-Bueno JM, Tiecher T. 2014a. Identificação de fontes de produção de sedimentos em uma bacia hidrográfica de encosta. *Revista Brasileira de Ciência do Solo* **38**:585-598.

Miguel P, Dalmolin RSD, Pedron FA, Moura-Bueno JM. 2014b. Variáveis mineralógicas preditoras de fontes de produção de sedimentos, em uma bacia hidrográfica do Rio Grande do Sul. *Revista Brasileira de Ciência do Solo* **38**:783-796.

Minella JPG, Walling DE, Merten GH. 2008. Combining sediment source tracing techniques with traditional monitoring to assess the impact of improved land management on catchment sediment yields. *Journal of Hydrology* **348**:546-563.

Minella JPG, Merten GH, Clarke RT. 2009b. Método “fingerprinting” para identificação de fontes de sedimentos em bacia hidrográfica rural. *Revista Brasileira de Engenharia Agrícola e Ambiental* **13**:633-638.

Minella JPG, Merten GH, Reichert JM, Santos DR. 2007. Identificação e implicações para a conservação do solo das fontes de sedimentos em bacias hidrográficas. *Revista Brasileira de Ciência do Solo* **31**:1637-1646.

Minella JPG, Merten GH, Walling DE, Reichert JM. 2009a. Changing sediment yield as an indicator of improved soil management practices in Southern Brazil. *Catena* 79:228-236.

Minella JPG, Walling DE, Merten GH. 2014. Establishing a sediment budget for a small agricultural catchment in southern Brazil, to support the development of effective sediment management strategies. *Journal of Hydrology* **519**:2189-2201.

Mizugaki S, Onda Y, Fukuyama T, Koga S, Asai H, Hiramatsu S. 2008. Estimation of suspended sediment sources using ^{137}Cs and $^{210}Pb_{ex}$ in unmanaged Japanese cypress plantation watersheds in southern Japan. *Hydrological Processes* **22**:4519-4531.

Navratil O, Evrard O, Esteves M, Legout C, Ayrault S, Némery J, Mate-Marin A, Ahmadi M, Lefèvre I, Poirel A, Bonté P. 2012. Temporal variability of suspended sediment sources in an alpine catchment combining river/rainfall monitoring and sediment fingerprinting. *Earth Surfaces Processes and Landforms* **37**:828-846.

Oliveira AH. 2011. *Erosão hídrica e seus componentes na sub-bacia hidrográfica do horto florestal Terra Dura, Eldorado do Sul (RS)*. Doctoral thesis, Universidade Federal de Lavras.

Olley J, Brooks A, Spencer J, Pietsch T, Borombovits D. 2013. Subsoil erosion dominates the supply of fine sediment to rivers draining into Princess Charlotte Bay, Australia. *Journal of Environmental Radioactivity* **124**:121-129.

Owens PN, Batalla RJ, Collins AJ, Gomez B, Hicks DM, Horowitz AJ, Kondolf GM, Marden M, Page MJ, Peacock DH, Petticrew EL, Salomons W, Trustrum NA. 2005. Fine-grained sediment in river systems: environmental significance and management issues. *River Research and Applications* **21**:693-717.

Palazón L, Gaspar L, Latorre B, Blake WH, Navas A. 2015. Identifying sediment sources by applying a fingerprinting mixing model in a Pyrenean drainage catchment. *Journal of Soils and Sediments* **15**:2067-2085.

Phillips JM, Russell MA, Walling DE. 2000. Time-integrated sampling of fluvial suspended sediment: a simple methodology for small catchments. *Hydrological Processes* 14:2589-2602.

Poleto C, Merten GH, Minella JPG. 2009. The identification of sediment sources in a small urban watershed in southern Brazil: An application of sediment fingerprinting. *Environmental Technology* **30**:1145-1153.

Poulenard J, Legout C, Némery J, Bramorski J, Navratil O, Douchin A, Fanget B, Perrette Y, Evrard O, Esteves M. 2012. Tracing sediment sources during floods using Diffuse Reflectance Infrared Fourier Transform Spectrometry (DRIFTS): a case study in a highly erosive mountainous catchment (Southern French Alps). *Journal of Hydrology* **414-415**:452-462.

Prosser IP, Rutherfurd ID, Olley JM, Young WJ, Wallbrink PJ, Moran CJ. 2001. Large-scale patterns of erosion and sediment transport in river networks, with examples from Australia. *Marine and Freshwater Research* **52**:81-99.

Ramgrab GE, Wildner W, Lopes RC, Favilla CAC, Silva MAS, Sachs LLB, Silva VA, Batista IH. 2004. Folha SH.22 – Porto Alegre. In: Schobbenhaus C, Gonçalves JH, Santos JOS, Abram MB, Leão Neto R, Matos GMM, Vidotti RM, Ramos MAB, Jesus JDA. (Eds.) *Carta Geológica do Brasil ao Milionésimo, Sistema de Informações Geográficas.* Programa Geologia do Brasil. Brasília, CPRM. Available in: <http://www.cprm.gov.br/publique/cgi/cgilua.exe/sys/start.htm?infoid=298andsid=26>.

Rauch HP, Sutili FJ, Hörbinger S. 2014. Installation of a riparian forest by means of soil bio engineering techniques - monitoring results from a river restoration work in Southern Brazil. *Open Journal of Forestry* **4**:161-169.

Rodrigues MF. 2011. *Monitoramento e modelagem de processos hidrossedimentológicos em bacias hidrográficas florestais no sul do Brasil*. Master thesis, Universidade Federal de Santa Maria.

Rodrigues MF, Reichert JM, Minella JPG, Dalbianco L, Ludwig RL, Ramon R, Rodrigues LA, Borges Júnior N. 2014. Hydrosedimentology of nested subtropical watersheds with native and eucalyptus forests. *Journal of Soils and Sediments* **14**:1311-1324.

Schuller P, Walling DE, Iroumé A, Quilodrán C, Castillo A, Navas A. 2013. Using ^{137}Cs and ^{210}Pb$_{ex}$ and other sediment source fingerprints to document suspended sediment sources in small forested catchments in south-central Chile. *Journal of Environmental Radioactivity* **124**:147-159.

Seeger M, Errea M, Begueria S, Arnaez J, Marti C, Garcia-Ruiz J. 2004. Catchment soil moisture and rainfall characteristics as determinant factors for discharge/suspended sediment hysteretic loops in a small headwater catchment in the Spanish Pyrenees. *Journal of Hydrology* **288**:299-311.

Silva AM. 2004. Rainfall erosivity map for Brazil. *Catena* **57**:251-259.

Simon A, Collison JCA. 2002. Quantifiying the mechanical and hydrological effects of riparian vegetation on stream banks stability. *Earth Surf Process Landforms* **27**, 527-546.

Smith HG, Sheridan GJ, Nyman P, Child DP, Lane PNJ, Hotchkis MAC, Jacobsen GE. 2012. Quantifying sources of fine sediment supplied to post-fire debris flows using fallout radionuclide tracers. *Geomorphology* **139-140**:403-415.

Smith HG, Evrard O, Blake WH, Owens PN. 2015. Preface - Addressing challenges to advance sediment fingerprinting research. *Journal of Soils and Sediments* **15**:2033-2037.

Strahler AN. 1957. Quantitative analysis of watershed geomorphology. *Transaction of American Geophysical Union* **38**:913-920.

Tiecher T. 2015. *Fingerprinting sediment sources in agricultural catchments in Southern Brazil*. Doctoral thesis, Universidade Federal de Santa Maria.

Tiecher T, Minella JPG, Miguel P, Alvarez JWR, Pellegrini A, Capoane V, Ciotti LH, Schaefer GL, Santos DR. 2014. Contribuição das fontes de sedimentos em uma bacia hidrográfica agrícola sob plantio direto. *Revista Brasileira de Ciência do Solo* **38**:639-649.

Tiecher T, Caner L, Minella JPG, Santos DR. 2015a. Combining visible-based-color parameters and geochemical tracers to improve sediment source discrimination and apportionment. *Science of the Total Environment* **527-528**:135-149.

Tiecher T, Caner L, Minella JPG, Bender MA, Santos D.R. 2015b. Tracing sediment sources in a subtropical rural catchment of southern Brazil by using geochemical tracers and near-infrared spectroscopy. *Soil & Tillage Research*, **155**:478-491.

USDA - United States Department of Agriculture. 1999. *Soil Survey Staff. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys*. 2nd ed. U.S. Department of Agriculture/Natural Resources Conservations Service, Washington, Agriculture Handbook. 871pp.

Walling DE, Collins AL. 2000. *Integrated assessment of catchment sediment budgets: A technical manual*. Exeter, University of Exeter. 168p.

Walling DE, Woodward JC. 1995. Tracing sources of suspended sediment in river basins: A case study of the River Culm, Devon, UK. *Marine and Freshwater Research* **46**:327-336.

Walling DE. 2013. The evolution of sediment source fingerprinting investigations in fluvial systems. *Journal of Soils and Sediments* **13**:1658-1675.

5 GENERAL DISCUSSION

Results of SWAT model calibration indicate processes occurring in nested and in paired watersheds are sensible to soil, land use, and topography parameters that exert control on the watershed system and on physical properties of the watersheds that are dependent on watershed size.

These parameters are not the most sensitive ones for most studies using SWAT (LELIS et al., 2012), but they seem to represent the processes occurring in our study areas and they are different on monthly and daily time-scales.

Monthly and daily observed and simulated streamflow matched well during calibration period for both nested (watershed and sub-watershed) and paired (grassland and eucalyptus) watersheds, where the performance to represent streamflow was considered better than “acceptable”, considering statistical parameters (MORIASI et al., 2007). On daily time-scale, streamflow statistical indicators were better for monthly than daily time-scale for the watershed and the sub-watershed. These results agree with those obtained by the other researchers studying different watersheds around the world (BONUMÁ et al., 2013; GREEN et al., 2006; MISHRA; SINGH, 2003; QIU; ZHENG; YIN, 2012; SETEGN et al., 2010; UZEIKA et al., 2012). However, for the grassland watershed and the eucalyptus watershed, streamflow statistical parameters were lower for monthly than daily time-scale. This behavior was observed by Quiao et al. (2015) in six paired experimental watersheds (three for grassland and three for forest encroached grassland).

However, streamflow processes can not be adequately represented, even when the statistical indicators had different trends on monthly and daily time-scales, comparing nested and paired watersheds. We expected better streamflow statistical indicators for monthly than daily time-scale, which was observed for the watershed and the sub-watershed, but not for the grassland and for the eucalyptus watersheds. Information obtained by SWAT simulation on monthly and daily time-scales is important to represent processes and may be used for natural resources management, because they adequately simulated the streamflow, according to statistical indicators; but the streamflow process needs to be analyzed on sub-daily time-scale when streamflow generation and propagation in fact are being measured at the watershed outlet. This recommendation is made because the effect of rainfall events and observed streamflow processes occur in a few hours in small watersheds (RODRIGUES et al., 2014; PELÁEZ, 2014).

SWAT was less effective in simulating sediment yield than streamflow, in both nested and paired watersheds. For sediment yield, the model was capable of simulating monthly and daily sediment yield only for the watershed, but was “unsatisfactory” to represent sediment yield for the sub-watershed. However, for paired watersheds, the model was effective in simulating monthly and daily sediment yield in the grassland watershed and in the eucalyptus watershed.

During the studied periods, for both nested and paired watersheds, SWAT model simulation showed sediment yield was, generally, underpredicted. This behavior occurred in nested watersheds, possible due to low sediment delivery ratio in each channel (RODRIGUES et al., 2014), and indicates that in-stream erosion/sedimentation might be of high importance in our studied watersheds.

We obtained “satisfactory” statistical indicators for sediment yield prediction, contrary to the observed by Uzeika et al. (2012) and Bonumá et al. (2013), where sediment yield using SWAT model was overpredicted. “Unsatisfactory” simulation of sediment yield results may be caused by limitations in sediment load equation or sediment propagation in the channel, due to the dependence on many empirical and semi-empirical equations. These findings indicate that equations to represent erosion processes need to be improved in the SWAT model, as also observed by Bonumá et al. (2013).

Our results shows that hydrological and sedimentological behavior of the watersheds is strongly dependent on soil properties, physical and morphological properties of the watershed, climate characteristics, and land use and management, and all these factors are site-specific and different for each watershed. Changes in sediment transport equations, such as proposed by Bonumá et al. (2013), are more important when erosion in rill and in inter-rill is high. However, our monitored sediment yield results and field experience shows that the main erosion processes occurs in the stream channel and coarse sediment is the main sediment type generated. This process needs to be considered and made more sensible in the SWAT model, and the sediment transport capacity needs to be evaluated considering the erosion processes and the type of sediment yielded occurring in the watershed. Equations based only on MUSLE apparently do not represent well the erosion processes occurring in the channel, especially when the sediment is mainly of coarse size.

The fingerprinting approach is useful to check results of SWAT model, by indicating the main sediment-source. The fingerprinting model of sediment-source classification was efficient to determine source contribution of fine sediments, but it was less efficient to determine source contribution of coarse sediments. Main source of fine-sediment and coarse-sediment was the bank channel. Eucalyptus had lower contribution of sediments than the bank channel and the unpaved roads, because of limited erosion and disaggregation of the surface soil. The lesser contribution of eucalyptus to fine and coarse sediment yield shows the effectiveness of surface litter and canopy protection (MIZUGAKI et al., 2008), runoff (MELLO; LIMA; SILVA, 2007) and erosion control in areas cropped to eucalyptus. Similarly to our results, Schuller et al. (2013) conducted sediment source fingerprinting studies in small forest watersheds and observed the dominant sediment-source was the stream channel (47%) during the period prior to clearcutting, whereas roads contributed 37% and watershed slopes only 16%. When evaluating the complete forest cycle, however, attention should be given to post-harvest and post-replanting periods, which were not evaluated in our study.

Sediment-source fingerprinting procedures have a significant potential to address these requirements for fine sediments, but improvements of fingerprinting procedures for coarse-sediments are necessary. This technique involves the discrimination of sediment sources and apportionment of contributions from sources to sediment transported within watershed stream network (SMITH et al., 2015). Most studies used <63 μm size fraction, but it is necessary to identify which sediment size-fraction is most frequent in the study area and what is the main impact of soil degradation and sediment generation to correctly evaluate sediment-sources.

The fingerprinting approach requires the selection of physical and chemical tracer properties that discriminate source materials combined with the use of statistical procedures to un-mix the unknown contributions from these sources to the mixture of sediment delivered downstream (SMITH et al., 2015). Watersheds sources widely considered by sediment fingerprinting studies include agricultural land uses, geological zones, and subsoil sources. To discriminate these sources, a diverse range of tracer properties may be employed, comprising geochemical, radionuclide, mineral magnetic, stable isotopes, organic compounds, and color properties (GUZMAN et al. 2013).

We used geochemical properties to evaluate both fine and coarse sediments. The model of sediment-sources classification had low efficient to determine source contribution of coarse sediments, where the relative error was greater than 15% for most sediment samples. These results show that complex dynamics of erosion imply the identification of sediment-sources and techniques types need improvement because coarse sediment has lower activity. An alternative is to combine both environmental and statistical approaches to tracer selection, with promising results to improve sediment-source identification as observed by Tiecher et al. (2015). They used visible-based-color parameters combined with classical geochemical properties as a rapid and inexpensive test to improve source discrimination and to improve the precision in sediment source apportionment.

The results of SWAT indicate the total amount of sediment yield generated in each sub-watersheds and HRUs, but it is not possible to identify which land uses are the main sources of fine and coarse sediment, or to quantify the stream channel contribution to sediment yield.

While the fingerprinting approach for coarse sediments needs further improvement, tracing of fine sediments is herein shown to provide additional information to the obtained from applying the SWAT model, when assessing the impact of land management on soil erosion and sediment yield in small watersheds.

6 GENERAL CONCLUSIONS

The ecohydrological model Soil and Water Assessment Tool (SWAT) was efficient in representing streamflow for small, paired and nested watersheds covered with eucalyptus and grassland, on monthly and daily time-scales. SWAT was efficient in describing sediment yield for small paired watersheds covered with eucalyptus stands and grassland on monthly and daily time-scales, while was less efficient to represent sediment yield for small nested watersheds.

The SWAT model is a promising tool to evaluate hydrology processes in paired watersheds in conditions of drastic changes in land use, and to evaluate hydrology processes in nested watersheds. However, to understand and to evaluate erosion and sedimentological processes in small, nested and paired watersheds covered with eucalyptus, in which the soil is protected and erosion processes are observed in other land uses or sediment-sources, more time and effort are required to set up and calibrate the model. SWAT needs to be improved to represent the erosion processes in each watershed and the type (fine or coarse) and amount of sediment generated, especially those processes not represented in MUSLE equations.

Fingerprinting approach is an efficient tool to identify fine sediment-source, whilst this approach is less efficient for coarse sediments. This result suggests fingerprinting approach needs to be improved to reduce uncertainty and identify coarse sediment-sources, where combining geochemical tracers to visible-based-color spectrum parameters and ultra-violet–visible spectrum might be an alternative.

Major fine and coarse sediment contributor was the stream channel, especially the bank channel. Sediment source apportionment results demonstrate that source contributions vary both with particle size and location within the watershed. The closer a sampling site is to a potential source, the more likely this source will dominate the material being sampled. For all size fractions, proximal sources of sediment are more likely to having a greater contribution to suspended sediments in the watershed.

Hydrosedimentological monitoring and modeling with SWAT indicated that eucalyptus provide low surface runoff, soil erosion and sediment yield in small watersheds, compared to watersheds with grassland land use. The model was efficient in representing hydrological processes, but was less efficient to represent sediment yield. Combining the fingerprinting approach to SWAT modeling provides a useful tool to assessing the impact of land management in soil erosion and sediment yields in small watersheds.

REFERENCES

ARNOLD, J. G. et al. Large area hydrologic modeling and assessment part I: model development. **Journal of American Water Resources Association,** v. 34, p. 73-89, 1998.

BONUMÁ, N. B. et al. Modeling surface hydrology, soil erosion, nutrient transport, and future scenarios with the ecohydrological SWAT model in Brazilian watersheds and river basins. In: Nascimento CWA, Souza Júnior VS, Freire MBGS, Souza ER (Org.). **Tópicos em Ciência do Solo**, IX: p. 241-290.

BONUMÁ, N. B. et al. Simulating landscape sediment transport capacity by using a modified SWAT Model. **Journal of Environmental Quality**, v. 43, p. 55-66, 2013.

Borah, D. K.; Bera, M. Watershed-scale hydrologic and nonpoint-source pollution models: Review of mathematical bases. **Transactions of the ASAE**, v. 46, p. 1553-1566, 2003.

Borah, D. K.; Bera, M. Watershed-scale hydrologic and nonpoint-source pollution models: Review of applications. **Transactions of the ASAE**, v. 47, p. 789-803, 2004.

BOSCH, J. M.; HEWLETT, J. D. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. **Journal of Hydrology,** v. 55, p. 3-23, 1982.

BRESSIANI, D. A. et al. Review of Soil and Water Assessment Tool (SWAT) applications in Brazil: Challenges and prospects. **International Journal of Agricultural and Biological Engineering,** v. 8, p. 9-35, 2015.

GREEN, C. H. et al. Hydrologic evaluation of the Soil and Water Assessment Tool for a large tile-drained watershed in Iowa. **Transactions of the ASABE**, v. 49, p. 413-422, 2006.

GUZMAN, G. et al. Sediment tracers in water erosion studies: current approaches and challenges. **Journal of Soils and Sediments,** v. 13, p. 816-833, 2013.

LELIS, T. A. et al. Análise de sensibilidade e calibração do modelo SWAT aplicado em bacia hidrográfica da região sudeste do Brasil. **Revista Brasileira de Ciência do Solo**, v. 36, p. 623-634, 2012.

MELLO, C. R.; LIMA, J. M.; SILVA, A. M. Simulação do deflúvio e vazão de pico em microbacia hidrográfica com escoamento efêmero. **Revista Brasileira de Engenharia Agrícola e Ambiental,** v. 11, p. 410-419, 2007.

MISHRA, S. K.; SINGH, V. P. **Soil Conservation Service Curve Number (SCS-CN) Methodology**. Dordrecht, The Netherlands: Kluwer Academic Publishers, 2003.

MORIASI, D.N. et al. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. **Transactions of the ASABE**, v. 50, p. 885-900, 2007.

PELÁEZ, J. J. Z. **Hidrologia comparativa em bacias hidrográficas com eucalipto e campo**. 2014. Tese (Doutorado em Engenharia Florestal), Universidade Federal de Santa Maria - RS, 2014.

QIAO, L. et al. Calibration of SWAT model for woody plant encroachment using paired experimental watershed data. **Journal of Hydrology**, v. 523, p. 231-239, 2015.

QIU, L.; ZHENG, F.; YIN, R. SWAT-based runoff and sediment simulation in a small watershed, the loessial hilly-gullied region of China: capabilities and challenges. **International Journal of Sediment Research**, v. 27, p. 226-234, 2012.

RODRIGUES, M. F. et al. Hydrosedimentology of nested subtropical watersheds with native and eucalyptus forests. **Journal of Soils and Sediments,** v. 14, p. 1311-1324, 2014.

SCHULLER, P. et al. Using ^{137}Cs and $^{210}Pb_{ex}$ and other sediment source fingerprints to document suspended sediment sources in small forested catchments in south-central Chile. **Journal of Environmental Radioactivity,** v. 124, p. 147-159, 2013.

SETEGN, S. G. et al. SWAT model application and prediction uncertainty analysis in the Lake Tana Basin, Ethiopia. **Hydrological Processes**, v. 24, p. 357-367, 2010.

SMITH, H. G. et al. Preface - Addressing challenges to advance sediment fingerprinting research. **Journal of Soils and Sediments,** v. 15, p. 2033-2037, 2015.

TIECHER, T. et al. Combining visible-based-color parameters and geochemical tracers to improve sediment source discrimination and apportionment. **Science of the Total Environment,** v. 527-528, p. 135-149, 2015.

UZEIKA, T. et al. Use of the SWAT model for hydro-sedimentologic simulation in a small rural watershed. **Revista Brasileira de Ciência do Solo,** v. 36, p. 557-565, 2012.