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MODELAGEM DO IMPACTO DO USO E MANEJO DO SOLO NOS PROCESSOS HIDROLÓGICOS E EROSIVOS EM PEQUENAS BACIAS HIDROGRÁFICAS

Santa Maria, RS
2022

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Tese apresentada ao Curso de Pós-Graduação em Ciência do Solo da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para a obtenção do título de **Doutor em Ciência do Solo**

Orientador: Prof. Dr. José Miguel Reichert

Santa Maria, RS
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Thais Palumbo Silva

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Sonhem! Sonhem alto! Sonhem com um mundo com menos corrupção, menos violência, menos terrorismo, mais igualdade social, mais harmonia e mais cidadania. Acreditem que o trabalho honesto pode fazer a diferença nesse sentido. Mas lembrem-se: O que torna um sonho irrealizável não é o sonho em si, mas sim, a inércia de quem sonha! Não sejam inertes!!

Alfredo Scheid (in memorian)

RESUMO

MODELAGEM DO IMPACTO DO USO E MANEJO DO SOLO NOS PROCESSOS HIDROLÓGICOS E EROSIVOS EM PEQUENAS BACIAS HIDROGRÁFICAS

AUTORA: Thais Palumbo Silva
ORIENTADOR: José Miguel Reichert

Os processos hidrológicos e de erosão do solo são afetados por inúmeros fatores, dentre eles, o uso e manejo do solo. Entender o impacto do uso e manejo do solo nos processos hidrológicos e erosivos na escala de bacias hidrográficas depende de diversas interações do ambiente. A modelagem hidrológica é uma importante estratégia, por possibilitar representar adequadamente essas interações no espaço e no tempo, através da detecção dos processos que atuam em diferentes escalas de tempo e simulação de cenários com diferentes condições. Diante disso, o objetivo deste trabalho foi contribuir para o entendimento do impacto do uso e manejo do solo nos processos hidrológicos e erosivos em pequenas bacias hidrográficas, por meio da combinação de técnicas de monitoramento e modelagem matemática. Foram realizados dois estudos em quatro pequenas bacias hidrográficas (~1 km^2), localizadas na região do Planalto e Campanha do Rio Grande do Sul. No primeiro estudo (artigo 1) foi quantificado o impacto do uso do solo na produção de sedimentos e água nas quatro pequenas bacias hidrográficas sob os três principais usos econômicos (agricultura, pastagem e floresta plantada) em três intervalos de tempo (mensal, diário e horário) utilizando o modelo *Soil & Water Assessment Tool* (SWAT). O modelo SWAT obteve um bom desempenho nas simulações em todas as bacias hidrográficas e intervalos de tempo. As bacias hidrográficas agrícolas apresentaram maior produção de sedimentos e água em relação as bacias sob pastagem e floresta plantada. Os principais processos hidrológicos detectados variaram nos diferentes intervalos de tempo e nas bacias hidrográficas, apresentando uma maior sensibilidade dos processos relacionados às propriedades dos solos na escala horária, e processos relacionados ao fluxo subsuperficial de água nas escalas de tempo mensal e diária. No segundo estudo (artigo 2) foram avaliados os efeitos das diferentes abordagens de práticas de conservação do solo e da água (práticas edáficas, vegetativas e mecânicas) nas bacias hidrográficas agrícolas: 9 cenários com práticas individuais e 4 com a associação das diferentes abordagens. A rotação de culturas e plantas de cobertura foi a prática individual de melhor eficiência em reduzir a produção de sedimentos em ambas as bacias hidrográficas. Os quatro cenários de associação das práticas conservacionistas mostraram ser mais eficaz, em especial a associação das três abordagens conservacionistas. A associação das três abordagens reduziu em até 60% da perda de solo nas sub-bacias das bacias agrícolas e também, otimizou os componentes do balanço hídrico. Os resultados dos dois estudos indicam que o uso e manejo dos solos são fatores que afetam diretamente os processos hidrológicos e de erosão do solo em diferentes escalas temporais e espaciais. Além disso, a modelagem hidrológica na escala de bacia hidrográfica é uma ferramenta viável para difundir o adequado manejo e uso do solo e reduzir os impactos da degradação do solo e da água.

Palavras-chave: SWAT. Dinâmica temporal. Práticas conservacionistas.

ABSTRACT

MODELING THE IMPACT OF LAND USE AND SOIL MANAGEMENT ON HYDROLOGICAL AND SOIL EROSION PROCESSES IN SMALL WATERSHEDS

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ADVISOR: JOSÉ MIGUEL REICHERT

Hydrological and soil erosion processes are affected by numerous factors such as land use and soil management. Understanding the impact of land use and management on hydrological and soil erosion processes at the watershed scale depends on several environmental interactions. Hydrological models are tools to represent these interactions in space and time by detecting the main processes in different time scales and by simulating scenarios with different conditions. Therefore, the objective of this study was to understand the impact of land use and soil management on hydrological and soil erosion processes in small watersheds through monitoring techniques and hydrological modeling. Two studies were carried out in four small watersheds (~1 km^2), located in the plateau and “Campanha” regions of Rio Grande do Sul state, Brazil. The first study (paper 1) quantified the impact of land use in four small watersheds under the three main economic uses (agriculture, pasture, and planted forest) in three-time steps (monthly, daily, and hourly) using the SWAT model. The SWAT model performed well in all watersheds and time steps. The agricultural watersheds showed the highest sediment and water yield values compared to Grassland and Planted Forest watersheds. The main detected hydrological processes varied in the different time steps and watersheds. Hourly dominant processes were linked to soil properties, and monthly and daily dominant processes were associated with subsurface water flow. The second study (paper 2) evaluated the effects of different conservation measures (soil management, vegetative practices and mechanical methods) in two paired agricultural watersheds: nine scenarios with individual conservation measures and four with association of the different conservation measures approaches. The crop rotation and cover crops were the best individual measures to reduce soil erosion in both watersheds. However, the association of conservation measures showed increased effectiveness to reduce sediment yield, especially the association of the three conservation approaches. The association of the three approaches reduced soil erosion by up to 60% in sub-watersheds and optimize water balance components. The outcomes of these studies indicate that land use and soil management are factors that directly affect hydrological and soil erosion processes in different time and space scales. Furthermore, modeling at the watershed scale is a viable tool to disseminate adequate land use and soil management, and to decrease impacts on soil and water degradation.

Keywords: SWAT. Temporal dynamics. Conservation measures.

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1 APRESENTAÇÃO

O crescimento global da população e da economia tem intensificado a exploração dos recursos naturais a fim de suprir a demanda por alimento, fibra e combustíveis (FAO, 2017). Entretanto, a expansão das áreas de cultivo altera os processos hidrológicos e de erosão do solo (MERTEN e MINELLA, 2013; BORRELLI et al., 2017). A erosão do solo pode ser considerada como o principal problema de degradação devido ao impacto negativo na produtividade das culturas e os danos causados aos cursos d'água e ao meio ambiente (BORRELLI et al., 2017). Para entender melhor os efeitos dos diferentes usos do solo nos processos hidrológicos e de erosão do solo, estudos integrados na escala de bacia hidrográfica têm expandido nas últimas décadas.

Os processos hidrológicos e de erosão do solo na escala de bacia hidrográfica são complexos, pois envolvem alta variabilidade quanto ao uso, manejo, solos, topografia e regime de chuva. Devido à complexidade do sistema, o entendimento desses processos pode ser facilitado por meio das técnicas de monitoramento e ferramentas de modelagem (de VENTE et al., 2013; WARDROPPER et al., 2017). Além disso, muitos estudos adotam a abordagem de bacias hidrográficas pareadas por consistirem em bacias com características similares que diferem apenas no uso do solo, possibilitando o melhor entendimento do impacto do uso na dinâmica hidrossedimentológica (BROWN et al., 2005).

A modelagem matemática é uma ferramenta importante que permite representar adequadamente a complexidade dos fatores envolvidos no espaço e no tempo. O modelo SWAT (Soil and Water Assessment Tool) é amplamente utilizado para simular os diferentes processos hidrossedimentológicos na escala de bacia hidrográfica (BRESSIANI et al., 2015; GASSMAN et al., 2014). Resultados de estudos utilizando o modelo SWAT têm demonstrado um bom desempenho na avaliação quantitativa de produção de água e sedimentos (LOPES et al., 2021; SERRÃO et al., 2021), identificação de áreas suscetíveis (BOUFALA et al., 2021; DIBABA et al., 2021), detecção dos processos dominantes no espaço e no tempo (GUSE et al., 2019; WU et al., 2020), impacto dos diferentes usos do solo (HU et al., 2021; LOPES et al., 2021; PENG et al., 2021), e simulação de práticas de conservação do solo e da água (STRAUCH et al., 2013; GASHAW et al., 2021; UNIYAL et al., 2020).

As atividades de uso do solo afetam propriedades que regem a geração de escoamento superficial e infiltração da água e propriedades relacionadas à suscetibilidade do solo e à erosão (NI et al., 2021; PENG et al., 2021; SERRÃO et al., 2021; YONABA et al., 2021). Por isso, é comum encontrar estudos que associem diretamente a perda de solo e água com o uso do solo.

Por exemplo, Serrão et al. (2021) investigaram o impacto da mudança de uso do solo e observaram que áreas sob cultivo agrícola e pastagem apresentaram maiores perdas de solo e água comparado com área sob floresta nativa. Valente et al. (2021) observaram menor produção de sedimentos e água na bacia pareada sob floresta plantada (eucalipto) do que na bacia pareada sob pastagem degradada. Polidoro et al. (2020) demonstrou que as áreas agrícolas sob cultivo anual no Brasil representam 5% do território total, porém contribuem com 59% da perda de solo total anual, seguida pela contribuição das áreas sob pastagem (~13%). Portanto, limitados estudos têm explorado o impacto dos três principais usos econômicos (agricultura, pastagem e floresta plantada) nas respostas hidrológicas e erosivas em escala de bacia hidrográfica.

De acordo com a FAO (2019), a erosão acelerada causada pela intensa agricultura tende a gerar maior perda de solo comparado com os demais usos do solo. Com isso, inúmeros esforços têm sido realizados para minimizar a perda de solo nessas áreas por meio da adoção de práticas de conservação do solo e da água. As práticas conservacionistas podem ser divididas em três abordagens: manejo do solo, práticas vegetativas e métodos mecânicos (BERTONI e LOMBARDI NETO, 2014), as quais trazem como funcionalidade aumentar a taxa de infiltração da água no solo, diminuir o impacto da gota de chuva, e diminuir a velocidade e volume do escoamento superficial, respectivamente. Muitos estudos concluíram que a associação das três abordagens é mais eficiente em conter a erosão do solo e o escoamento superficial (EBABU et al., 2019; GASHAW et al., 2021; LÓPES-BALLESTEROS et al., 2019; UNIYAL et al., 2020). No entanto, devido à alta resistência dos produtores rurais em adotar tais medidas, torna-se interessante avaliar o efeito dessas abordagens separadamente para obter subsídios na escolha das práticas mais viáveis e apropriadas em diferentes condições.

Diante do exposto, a tese consiste em dois estudos, com o objetivo geral de compreender o impacto dos diferentes usos e manejos do solo nos processos hidrológicos e erosivos em bacias hidrográficas pareadas e em diferentes escalas temporais. O primeiro estudo (artigo 1) avaliou a dinâmica dos processos hidrológicos e de erosão do solo em quatro pequenas bacias hidrográficas sob diferentes usos: agricultura, pastagem e floresta plantada, nas escalas de tempo mensal, diária e horária, utilizando o modelo SWAT. O segundo estudo (artigo 2) avaliou a eficácia da implementação de diferentes abordagens conservacionistas na redução da produção de sedimentos e na melhoria dos processos hidrológicos.

2 HIPÓTESES E OBJETIVOS

2.1 HIPÓTESES

- A dinâmica dos processos hidrológicos e de erosão do solo é afetada pelo uso do solo e varia nas diferentes escalas temporais em pequenas bacias hidrográficas, sendo que as bacias hidrográficas sob agricultura são mais suscetíveis a alterações nos processos hidrológicos e de erosão do solo.
- A implementação das diferentes abordagens de conservação do solo e da água (edáficas, vegetativas e mecânicas) é eficiente em reduzir a produção de sedimentos e potencializar os componentes do balanço hídrico, sendo que as práticas mecânicas são mais eficazes.

2.2. OBJETIVO GERAL

Contribuir para o entendimento do impacto do uso e manejo do solo nos processos hidrológicos e erosivos em pequenas bacias hidrográficas, a partir da combinação de técnicas de monitoramento e modelagem matemática.

2.3. OBJETIVOS ESPECÍFICOS

- Quantificar o impacto do uso do solo em quatro bacias sob os três principais usos econômicos (agricultura, pastagem, floresta plantada);
- Identificar os principais processos hidrossedimentológicos que atuam nas escalas de tempo mensal, diária e horária por meio do modelo SWAT;
- Avaliar a eficiência de cada abordagem de práticas de conservação do solo e da água de forma separada em reduzir a produção de sedimentos;
- Avaliar o efeito da associação das práticas de conservação do solo e da água nos componentes do balanço hídrico.

3 ARTIGO 1- EVALUATING TEMPORAL HYDROLOGIC AND SOIL EROSION RESPONSES TO SMALL WATERSHEDS UNDER DIFFERENT LAND USES IN SOUTHERN BRAZIL

(Artigo elaborado de acordo com as normas da revista *Journal of Hydrology*)

Abstract

Land use activities are dominant driving factors to hydrological and soil erosion responses in the watershed scale. Understanding temporal hydrossedimentological dynamics in watersheds under different land uses can facilitate the development of sustainable water and soil resource management. This study aimed to assess the hydrological and soil erosion processes on small watersheds under three different main economic land uses (cropland, grassland, and planted forest) at three-time scales (monthly, daily, and hourly). We investigated four small watersheds (~1 km^2) located in southern Brazil: Agricultural North watershed (ANW), Agricultural South watershed (ASW), Eucalyptus watershed (EW), and Grassland watershed (GW). Hydrossedimentological monitoring was carried out from 2016 to 2019 for ANW and ASW, and from 2011 to 2019 for EW and GW. Soil and Water Assessment Tool (SWAT) model was used to simulate streamflow (SF) and sediment yield (SY) in three-time scales. Then, we evaluated the correlation between the hydrossedimentological variables (rainfall, streamflow and sediment yield) and identified the dominant processes for each time scale. The EW had the lowest streamflow and sediment yield than the other three watersheds, whereas ANW and ASW showed the highest sediment yield and streamflow. The SWAT model had a satisfactory performance in all time scales and watersheds for streamflow and sediment yield. The most sensitive hourly parameters were soil properties, and the monthly and daily parameters were linked to subsurface water flow for all watersheds. Streamflow showed positive correlation with rainfall and sediment yield. Overall, land use activities have a major impact on hydrological and soil erosion responses. Understanding these impacts for the different land uses and into each temporal scale is necessary to provide valuable information for better land use planning and to adopt soil and water conservation measures.

Keywords: land use activities, SWAT, hydrossedimentological temporal dynamics.

3.1 INTRODUCTION

The current global growth of population and economy has increased demands on agriculture leading to more intense competition for natural resources, and consequently triggering deforestation and land degradations (FAO, 2017). Hydrological and soil erosion processes are affected by many factors, such as land use activities (Ni et al., 2021; Peng et al., 2021; Yonaba et al., 2021). Studies have demonstrated that land use affects different hydrological processes such as infiltration (Anderson et al., 2020; Sun et al., 2018), groundwater recharge (Ghimire et al., 2021; Yifru et al., 2021), evapotranspiration (Hu et al., 2021), soil water content (Lopes et al., 2021; Mallet et al., 2020), water yield (Hu et al., 2021; Lopes et al., 2021), and sediment yield (Ni et al., 2021; Risal et al., 2020; Serrão et al., 2021).

In recent years, several studies have been developed to understand the effect of different land uses on hydrossedimentological processes (Ebling et al., 2021a; Li et al., 2021; Lopes et al., 2021; Peng et al., 2021; Serrão et al., 2021; Valente et al., 2021). Previous studies showed a decrease in streamflow and sediment yield to planted forest compared to grassland watershed (Reichert et al., 2017; Valente et al., 2021). Besides the large canopy and presence of litter layer in forests (Ferreto et al., 2021a), it has been shown that watersheds under forest have increased evapotranspiration (Hu et al., 2021; Reichert et al., 2017, 2021a, 2021b), higher infiltration rate (Anderson et al., 2020), lower surface runoff (Hu et al., 2021; Li et al., 2021; Reichert et al., 2017) and lower soil erosion (Ebling et al., 2021a; Valente et al., 2021) in relation to other land uses. On the other hand, in cropland and grassland areas intense management activities occur by tillage and livestock, which increases water and sediment yield (Serrão et al., 2021; Tiecher et al., 2018; Valente et al., 2020). However, no studies have been carried out to assess the impact of the three main economic land uses (cropland, grassland, and planted forest) on hydrological and soil erosion processes at watersheds scales.

In southern Brazil, the economic land use activities have exponentially increased in the last decades. According to IBGE (2019), the land use activities of Rio Grande do Sul State consist of a total area of 21.7 million hectares, of which 42% are grassland, 36% cropland, and 4% planted forest. In the last years, changes have occurred with an increase of cropland (2%) and planted forest and a decrease in grassland (3.3%) (AGEFLOR, 2020). Eucalyptus plantations (68% of the total planted forest area) have been the main responsible for the expansion of planted forest areas in Rio Grande do Sul (AGEFLOR, 2020). These land use activities linked to different soil classes and high rainfall in southern Brazil have been raising concerns on environmental sustainability associated with hydrological processes responses (Bonumá et al., 2013; de Barros et al., 2020; Ferreto et al., 2021b; Reichert et al., 2017, 2021b), soil erosion and sedimentation (Bonumá et al., 2014; de Barros et al., 2021; Didoné et al., 2014; Ebling et al., 2021a, 2021b; Minella et al., 2014; Rodrigues et al., 2014, 2018; Valente et al., 2020, 2021;), water quality (Becker et al., 2009; de Bastos et al., 2021; Didoné et al., 2021b; Fernandes et al., 2019; Kaiser et al., 2010, 2015), and the effects of soil conservation measures (Didoné et al., 2015, 2017, 2021a; Londero et al., 2018; Reichert et al., 2019, 2021c).

Nowadays, studies about the impact of land use activities on watershed hydrology and soil erosion have received increased attention. The most common approach to understanding the influence of land use at watershed scales is to study paired watersheds and hydrological modeling (Hu et al., 2021; Reichert et al., 2021a). The paired watershed approach consists of studying two watersheds with similar characteristics that differ only on land use (Brown et al., 2005), and hydrological models have a key role to play in understanding complex environmental phenomena in space and time. For modeling, Soil and Water Assessment Tool (SWAT) has been proved to be efficient to predict hydrological and soil erosion responses to different land uses (Bressiani et al., 2015a; Gassman et al., 2014; Hu et al., 2021; Lopes et al., 2021; Ni et al., 2021; Peng et al., 2021).

Modeling is an effective tool for detailed temporal scale analysis to detect the main processes in short- and long-term (Baffaut et al., 2015; Wu et al., 2020). The capability of simulating in lower time scale is important for small watersheds to adequately capture hydrological processes between short time intervals, while higher time scale simulating is also necessary to investigate long term impacts of land use and climate change and evaluate slower processes (Gentine et al., 2012). In general, characteristics of water and sediment yield also differ considerably with the change of time scales, and both are closely interconnected.

It is still challenging in watershed models to reproduce temporal variability of hydrological and soil erosion processes (Guse et al., 2019; Singh and Jha, 2021). However, this is required to identify specific processes in each time scale of the calibrated model and further, to develop future scenarios evaluating the impacts of land use changes. Therefore, the objectives of this study were (i) to compare characteristics of four watersheds under cropland, grassland and planted forest that contribute to different hydrological and soil erosion responses, (ii) to evaluate the ability of the SWAT model to simulate water and sediment yield in three-time scales (monthly, daily and hourly), (iii) to identify the most sensitive parameters for each time scale and watershed, (iv) to understand the dynamics of water and sediment yield in each time scale, and (v) to understand the impact of land use on hydrological and soil erosion processes responses in the four watersheds.

3.2 MATERIAL AND METHODS

3.2.1 Study watersheds

The study watersheds can be classified by three main economic land uses under different soil types and with high annual precipitation. Four watersheds were selected for this study, they are spatially distributed in southern Brazil (Rio Grande do Sul state) and cover different land uses: Cropland, Grassland and Eucalyptus (Figure 1). There are two paired cropland watersheds, namely Agricultural North Watershed (ANW) and Agricultural South Watershed (ASW), located in the physiographic plateau region in southern Brazil, municipality of Quinze de Novembro (Figure 1a). These watersheds belong to the Alto Jacuí watershed. Both watersheds are under grain cropland, grassland and native forest, differing in size, percentage of each land use (Table 1) and soil properties (Table 2). Another two paired watersheds, Eucalyptus watershed (EW) and Grassland watershed (GW), are located in the Campanha physiographic region in southern Brazil, municipality of São Gabriel (Figure 1d). These watersheds belong to the Vacacaí-Vacacaí Mirim watershed. The EW is covered by planted Eucalyptus (*Eucalyptus saligna*) managed by the CMPC Riograndense Cellulose company, and GW is covered by degraded grassland and livestock farming.

According to Köppen climate classification, the climate of these regions is humid subtropical (Cfa), with an average annual temperature of 18.5ºC and an average annual rainfall of 1,356 mm (Alvares et al., 2013).

Soils in ANW and ASW were developed from basaltic volcanic rock. The soils are classified according to the World Reference Base (FAO, 2015) as Ferralsols, Acrisols, Nitisols, Leptosols, and Gleysols (Figure 1c) (Tornquist, 2007), and the land uses were soybean (*Glycine max*), corn (*Zea mays*), native forest and grassland (*Cynodon dactylon* – TifMg 85) (Figure 1b), in which agricultural cropland is under no-till. The soils in EW and GW were developed from metamorphic and granite-gneiss rocks, classified as Acrisols, Cambisols, and Leptosols (only EW) (Figure 1f) (Peláez, 2014). Land uses in EW correspond to plantations of *Eucalyptus saligna*, 61% of total area (40% was planted in 2006 and 21% in 2014, after harvest operations), native grassland, and native forest. In the GW, the main land uses consist of degraded native grassland, oats pasture (*Avena strigosa*), patches and isolated individuals of Eucalyptus and native forest (Figure 1e).

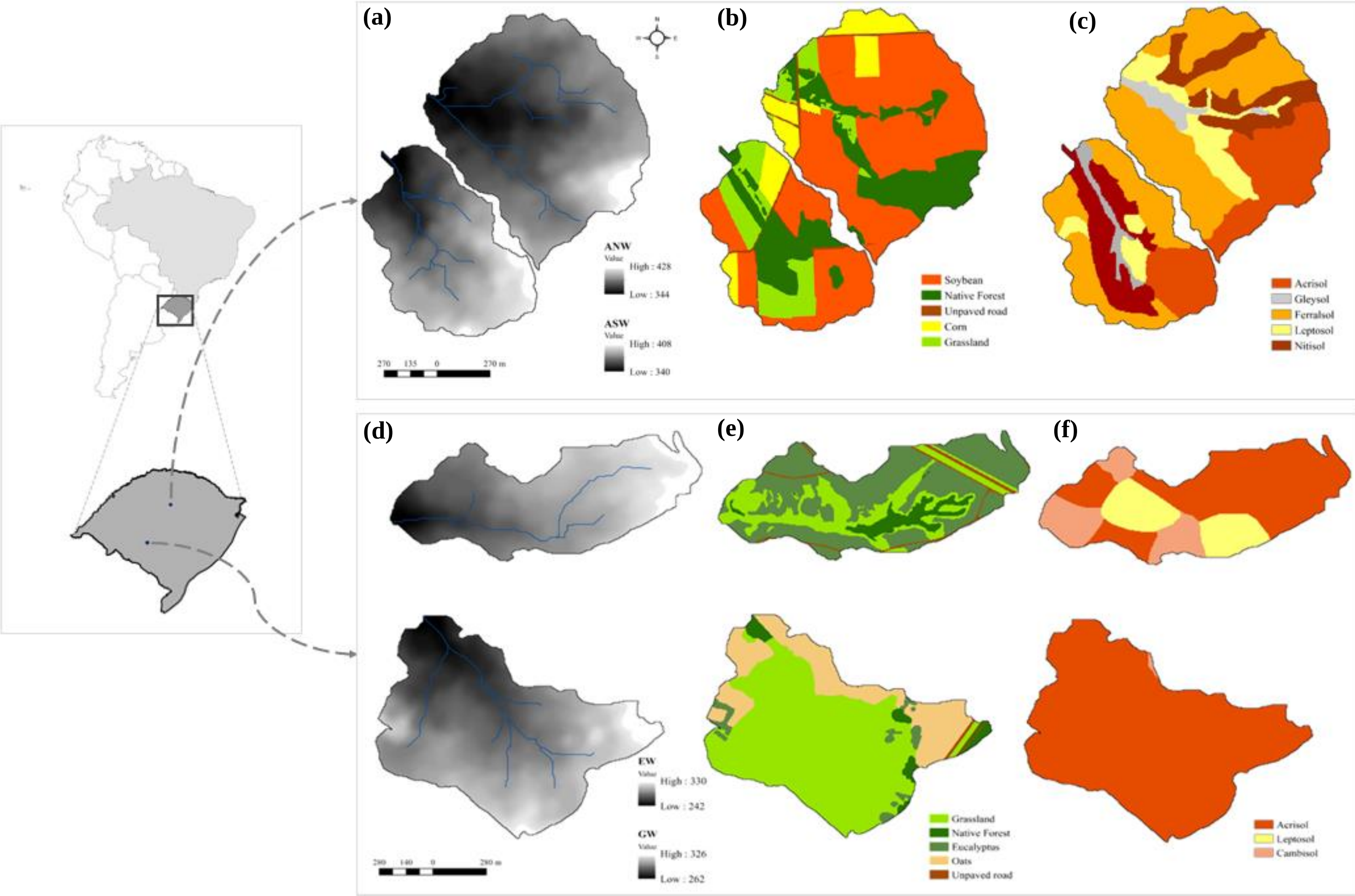


Figure 1. Location of Agricultural North watershed (ANW), Agricultural South watershed (ASW), Eucalyptus watershed (EW) and Grassland watershed (GW) and (a,d) elevation map, (b,e) land use map, and (c,f) soil map. Source: ASF Data Search (2019), Tornquist (2007) and Peláez (2014).

3.2.2 Hydrological and soil erosion monitoring

Monitoring was conducted from May 2016 to December 2019 for ANW and ASW, and from January 2011 to December 2019 for EW and GW, using automated monitoring gauge sections. The monitoring sections are located in each watershed outlet, which is equipped with measuring instruments of rainfall (pluviographs), water level (limnigraphs), and turbidity sensors (turbidimeters), connected to data loggers that recorded data every 10 minutes. Suspended sediment concentration (SSC) was estimated using a calibration curve equation obtained from the relation between turbidity and SSC from manually-collected samples during rainfall-runoff events (Ebling, 2018; Valente, 2018). Sediment yield (Mg) (SY) was calculated by multiplying streamflow (L s^{-1}) and SSC (mg L^{-1}). In addition, the continuous automated monitoring was prone to some short-term missing gaps due to recording failures. To obtain more reliable information for the rainfall data, gaps were filled using data from the monitoring section of the paired watershed when available, or from the Inmet (Brazilian National Institute of Meteorology) station. The recording failures are 17, 16, 13 and 3% for ANW, ASW, EW and GW, respectively.

This study was conducted on three-time scales: monthly, daily, and hourly. Average streamflow and sum of rainfall and sediment yield were calculated for each time step. Then, Pearson correlation analysis was carried out in each time scale between rainfall, streamflow, and sediment yield to investigate their levels of correlation for each watershed.

3.2.3 Hydrological and soil erosion modeling

3.2.3.1 Description of SWAT model

We used the Soil and Water Assessment Tool (SWAT) model to evaluate hydrological and soil erosion responses of watersheds under different land uses. The SWAT is a physically-based, continuous-time and semi-distributed hydrological model that has been widely used to understand the impacts of land uses and management practices on water, sediment and agricultural chemical yields at watershed scale (Arnold et al., 1998; Arnold et al., 2013). In SWAT, the watershed is divided into sub-basins based on DEM data; further, each sub-basin is subdivided into hydrologic response units (HRUs), consisting of homogeneous land use, soil type and slope. SWAT simulates each hydrological and erosion process at HRU level and it is aggregated at a sub-basin level. There are two methods for computing surface runoff volume and sediment yield: Soil Conservation Service curve number (Soil Conservation Service, USDA 1972) and Green and Ampt infiltration method for daily and hourly surface runoff, respectively, and Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975), and splash erosion and erosion by surface runoff methods for daily and sub-daily sediment yield. More details about sub-daily equations can be found at Jeong et al. (2010, 2011).

The hydrological cycle as simulated by SWAT is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=t}^{t}(R_{day} - Q_{surf} - ET - w_{seep} - Q_{sub}) \quad (1)$$

where SW_t is the final soil water content (mm H_2O); SW_0 is the initial soil water content on the *i*-th day (mm H_2O); t is the time (days); R_{day} is the amount of rainfall on the *i*-th day (mm H_2O); Q_{surf} is the amount of surface runoff on the *i*-th day (mm H_2O); ET is the amount of evapotranspiration on the *i*-th day (mm H_2O); w_{seep} is the amount of water entering the vadose zone from the soil profile on the *i*-th day (mm H_2O); and Q_{sub} is the amount of return flow on the *i*-th day (mm H_2O).

3.2.3.2 SWAT model setup

The SWAT model was used to simulate streamflow and sediment yield from 2016 to 2019 for ANW and ASW, and from 2012 to 2019 for EW and GW, with a warm-up period from 2014 and 2015 for ANW and ASW, and from 2010 and 2011 for EW and GW. The four watersheds were split into 17, 10, 7, and 11 sub-basins, including 350, 268, 142, and 99 HRUs for ANW, ASW, EW, and GW, respectively. The Soil Conservation Services curve number (SCS-CN) and Green and Ampt Infiltration method were employed for daily and hourly runoff simulation, respectively. Priestley-Taylor method was used to simulate potential evapotranspiration for ANW and ASW, and Penman-Monteith method for EW and GW. The Modified Universal Soil Loss Equation (MUSLE) and Erosion by rainfall and surface runoff methods were used to calculate daily sediment yield and hourly suspended sediment concentration, respectively. On hourly time scale, SWAT simulates the SSC instead of SY as on daily time scale.

Moreover, SWAT requires the data sets of Digital Elevation Map (DEM), meteorology, soil and land use. The DEM was obtained from Alaska Satellite Facility (ASF, 2019) with a spatial resolution of 12.5 meters. Then, a DEM with 5 meters was generated by contouring vectors in the GIS tool for each watershed. The slope map was divided in four classes: 0-2%, 2-8%, 8-15%, and > 15%. Soil data with a scale of 1:10,000 and soil properties, such as soil granulometry, bulk density, total porosity, soil organic carbon, saturated hydraulic conductivity, and available water content for each soil horizon were obtained from the measured properties by Tornquist (2007) and Ebling (2018) for ANW and ASW, and by Peláez (2014) and Morales (2013) for EW and GW. Soil erodibility and soil albedo were determined with equation proposed by Denardin (1990) for Brazilian soils and Post et al. (2000), respectively. Soil data information for each soil and horizon was added to the SWAR user soils databases (.usersoil file).

The land use maps were created from interpretation and classification of Landsat satellite images (Landsat8/OLI images) and confirmed in a field survey. For the native forest and Eucalyptus, crop parameters such as initial leaf area index, initial biomass, total number of heats units needed for growth, and minimum and maximum values of leaf area index were adjusted to better fit the conditions of the area (.landcover file). Meteorological daily data (precipitation, maximum and minimum temperature, wind speed, solar radiation and relative humidity) was obtained at a station located in the municipally (Ibirubá for ANW and ASW, and São Gabriel for EW and GW) of each paired watershed from the Brazilian National Institute of Meteorology (Inmet, 2020). For monthly, daily, and hourly simulations, the precipitation data was input in a time step of 60 minutes.

3.2.3.3 Model sensitivity, calibration and validation

A multi-step procedure was employed for calibration and validation (Bressiani, 2016). The first step was to calibrate and validate streamflow from monthly to hourly time scale. Then, the calibration and validation of sediment yield were carried out in the same time order. First, the simulating periods were divided into calibration and validation with similar hydrological behavior. Data from the period of 2016, 2018 and 2019 (ANW and ASW) and from 2012 to 2016 (EW and GW) were used for calibration and, data of 2017 (ANW and ASW) and from 2017 to 2019 (EW and GW) were used for model validation. Semi-automatic sensitivity analysis, calibration and validation of streamflow and sediment yield was performed using the Sequential Uncertainty Fitting algorithm version 2 (SUFI-2) within SWAT Calibration Uncertainty Procedure (SWAT-CUP) (Abbaspour et al., 2007). Nash-Sutcliffe (NSE) was chosen as the objective function. Therefore, the hourly calibration for streamflow and suspended sediment concentration was done through a component to extract the data from the sub-daily output format from SWAT incorporated into SWAT-CUP developed by Bressiani (2016).

Definition of calibration parameters and ranges for streamflow and sediment yield was based on SWAT calibration literatures (Abbaspour et al., 2007, 2015; Arnold et al., 2012; Jeong et al., 2011), the modeler experience and previous studies conducted in the studied watersheds (Rodrigues, 2015). A global sensitivity analysis was implemented to identify parameters significantly influencing streamflow and sediment yield in each time step. In this analysis, all parameters are allowed to change at the same time followed by estimating the standardized regression coefficients (Abbaspour, 2008). The p-value was used to evaluate the significance of relative sensitivity, in which p-value close to zero represents higher significance (Abbaspour, 2008). Table 3 lists all calibrated parameters for each time step, variable and watershed.

3.2.3.4 Model performance evaluation

The performance of SWAT was evaluated based on statistical indicators and performance rating according to Moriasi et al. (2007), for streamflow and sediment yield simulations. The statistical indicators were: Nash-Sutcliffe Efficiency (NSE), Percent Bias (P_{bias}) and coefficient of determination (R^2).

$$R^2 = \left[\frac{\sum_{i=1}^{n}(Y_{obs} - \overline{Y_{obs}})(Y_{sim} - \overline{Y_{sim}})}{\sqrt{\sum_{i=1}^{n}(Y_{sim} - \overline{Y_{sim}}) * \sum_{i=1}^{n}(Y_{obs} - \overline{Y_{obs}})}}\right]^2 \quad (2)$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_m^{obs}\right)^2}\right] \quad (3)$$

$$P_{bias} = 100 * \frac{\sum_{i=1}^{n}(Y_{obs} - Y_{sim})^2}{\sum_{i=1}^{n}(Y_{obs} - \overline{Y_{sim}})^2} \quad (4)$$

where Y_{sim} is simulated value from the model, $\overline{Y_{sim}}$ is average value between the simulated values, Y_{obs} is observed value in the field, and $\overline{Y_{obs}}$ is average value between the measured data. R^2 ranges from 0 to 1 and quantifies the proportion of explained variance in observed data, with higher values indicating less error variance. NS estimates the relative magnitude of residual variance as compared to observed data (Nash and Sutcliffe, 1970), and P_{bias} can indicate model performance and measures the average tendency of simulated data to be larger or smaller than observed data. Positive values of P_{bias} indicate the model underestimation, and negative values indicate the model overestimation.

3.3 RESULTS

3.3.1 Comparison of watersheds characteristics

The watershed characteristics related to monitored data, topography, land use, and soils of watersheds are compared in Table 1. Annual average rainfall was computed from 2016 to 2019 for ANW and ASW, and from 2012 to 2019 for EW and GW. There is a difference of only 168.8 mm yr^{-1} (~11%) from highest (ASW) to lowest average annual rainfall (GW). In observed data, the highest average streamflow was found in ASW, and the highest sediment yield was in ANW. Drainage areas vary from 0.54 km^2 (ASW) to 1.006 km^2 (GW). The average slopes of watersheds are almost similar, in which Agricultural paired watersheds have greater slope than Eucalyptus and Grassland paired watersheds.

Table 1. Physical watershed characteristics of Agricultural North watershed (ANW), Agricultural South watershed (ASW), Eucalyptus watershed (EW), and Grassland watershed (GW).

Main watershed characteristics	Watersheds characteristics	ANW	ASW	EW	GW
Monitored data (2016-2019 / 2012-2019)	Average annual rainfall	1330.17	1490.7	1465.55	1321.9
	Average streamflow (m^3 s^{-1} km^{-2})	0.023	0.044	0.012	0.024
	Average sediment yield (Mg km^{-2})	0.0154	0.0041	0.0004	0.0013
Topography	Area (km^2)	0.94	0.54	0.73	1.00
	Average slope (%)	9.75	9.38	8.27	7.57
	Elevation (meters)	342-429	340-408	242-330	262-326
Land use	Grassland (%)	3.6	22.5	27.6	67.8
	Eucalyptus (%)	0.0	0.0	61.4	3.2
	Unpaved Road (%)	1.4	1.5	3.6	0.7
	Native Forest (%)	22.1	24.1	7.5	3.6
	Oats (%)	0.0	0.0	0.0	24.7
	Corn (%)	11.7	8.3	0.0	0.0
	Soybean (%)	60.3	43.7	0.0	0.0
Soils	Acrisols (%)	24.2	19.6	59.5	99.7
	Cambisols (%)	0.0	0.0	19.5	0.3
	Leptosols (%)	12.4	7.7	21.1	0.0
	Gleysols (%)	4.1	6.2	0.0	0.0
	Ferralsols (%)	43.4	39.4	0.0	0.0
	Nitisols (%)	15.9	27.2	0.0	0.0

Source: ASF Data Search (2019), Tornquist (2007) and Peláez (2014).

Land use is the major difference in the four studied watersheds. The EW and GW have 61% and 68% of total area under *Eucalyptus saligna* and grassland, respectively. The EW has 50% more of native forest than the GW. Agricultural paired watersheds differ in the percentage of cropland area and native forest, ANW has over 38% of cropland and less than 8% of native forest than ASW.

A large difference in soil properties between the four watersheds, and between the paired watersheds is observed (Table 2). The GW and EW are covered by Acrisols, Cambisols, and Leptosols (only EW). These soils are characterized as shallow sandy soils with a high saturated hydraulic conductivity. The predominant soil in Eucalyptus and Grassland watersheds, Acrisols, has high sand contents in Ap horizon (63% and 61%, respectively) and high clay contents in Bt horizon (56% and 45%, respectively) (Morales, 2013). Both Agricultural paired watersheds (ANW and ASW) have the same soils (Ferralsols, Acrisols, Nitisols, Leptosols, and Gleysols). Hence, there are significant differences in soil attributes properties. The ANW has deeper soils, higher saturated hydraulic conductivity, and higher clay content than ASW (Table 2). These soil properties can influence hydrological and sedimentological cycle components in each watershed (Bouslihim et al., 2019; Krpec et al., 2020).

Table 2. Average soil properties values of Agricultural North watershed (ANW), Agricultural South watershed (ASW), Eucalyptus watershed (EW), and Grassland watershed (GW).

Soil	Soil depth				BD (g/cm³)				AWC (mm)				SAT (mm/h)				Clay-Silt-Sand (%)			
	ANW	ASW	EW	GW	ANW	ASW	EW	GW	ANW	ASW	EW	GW	ANW	ASW	EW	GW	ANW	ASW	EW	GW
Acrisols	2800	1700	1000	1000	1.59	1.47	1.42	1.45	0.16	0.17	0.15	0.16	29.35	8.05	103.15	99.78	22-10-68	36-10-54	40-15-45	29-19-52
Cambisols	-		1000		-		1.51		-		0.14		-	-	26.36		-		24-19-57	
Leptosols	1000		1000	-	1.61		1.45	-	0.16		0.11	-	29.90		700.80	-	42-28-30	42-28-30	16-17-67	-
Gleysols	2450	500	-		1.35	1.47	-		0.24	0.15	-		106.18		-		30-21-49	19-12-69	-	
Ferralsols	3400	1000	-		1.29	1.42	-		0.15	0.15	-		31.33	15.03	-		54-25-21	48-28-24	-	
Nitisols	3200	1000	-		1.36	1.45	-		0.18	0.13	-		66.44	7.58	-		43-37-20	60-22-18	-	

Source: Morales (2013) and Ebling (2018).

3.3.2 Hydrological and soil erosion modeling

3.3.2.1 Model parameter sensitivity analysis

Sensitivity analysis of the model parameters was implemented to identify the parameters that significantly influence the streamflow and sediment yield simulation in each time step. In general, twenty-one and eleven parameters were selected for the SWAT-CUP semi-automatic calibration to simulate streamflow and sediment yield, respectively (Table 3). However, the parameters used varied in each time step and watersheds. The significance of sensitive parameters on simulated variables was evaluated by p-value (Figure 2).

Table 3. Lower and Upper range of the SWAT parameters selected for monthly, daily, and hourly time scale for Agricultural North watershed (ANW), Agricultural South watershed (ASW), Eucalyptus watershed (EW), and Grassland watershed (GW).

Calibrated variable	Parameters	Name[a]	Lower range	Upper range
Streamflow	Baseflow alpha factor (days)	v__ALPHA_BF.gw	0.01	0.50
	Maximum canopy storage (mm H2O)[b]	v__CANMX.hru	0.00	30.00
	Effective hydraulic conductivity in main channel alluvium (mm/hr)	r__CH_K2.rte	-0.20	0.20
	Manning's "n" value for the tributary channels	r__CH_N1.sub	-0.20	0.20
	Manning's "n" value for the main channel	r__CH_N2.rte	-0.20	0.20
	SCS runoff curve number	r__CN2.mgt	-0.15	0.15
	Plant uptake compensation factor[c]	v__EPCO.hru[c]	0.01[c]	0.50[c]
	Soil evaporation compensation factor	v__ESCO.hru	0.70	0.90
	Groundwater delay time (days)	v__GW_DELAY.gw	0.00	250.00
	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H2O)	v__GWQMN.gw	0.00	5000.00
	Groundwater "revap" coefficient	v__GW_REVAP.gw	0.02	0.10
	Average slope steepness (m/m)	r__HRU_SLP.hru	-0.10	0.10
	Lateral flow travel time (days)	v__LAT_TTIME.hru	0.00	15.00
	Manning's "n" value for overland flow	r__OV_N.hru	-0.20	0.20
	Deep aquifer percolation fraction	v__RCHRG_DP	0.00	0.10
	Average slope length (m)	r__SLSUBBSN.hru	-0.10	0.10
	Slope length for lateral subsurface flow (m)	v__SLSOIL.hru	0.00	150.00
	Available water capacity of the soil layer (mm H2O/mm soil)	r__SOL_AWC.sol	-0.20	0.20
	Moist bulk density (g/cm3)	r__SOL_BD.sol	-0.20	0.20
	Saturated hydraulic conductivity (mm/hr)	r__SOL_K.sol	-0.20	0.20
	Surface runoff lag coefficient	v__SURLAG.hru	0.00	24.00

Sediment yield	Channel erodibility factor	v__CH_COV1.rte	0.00	0.60
	Channel cover factor	v__CH_COV2.rte	0.00	1.00
	Peak rate adjustment factor for sediment routing in the main channel	v__PRF_BSN.bsn	0.00	2.00
	Linear parameter for maximum amount of sediment reentrained in channel sediment routing	v__SPCON.bsn	0.00	0.01
	Exponent parameter for calculating sediment reentrained in channel sediment routing	v__SPEXP.bsn	1.00	1.50
	Exponential coefficient for overland flow	v__EROS_EXPO.bsn	1.20	3.00
	Rill erosion coefficient	v__RILL_MULTI.bsn	0.50	2.00
	Scaling parameter for cover and management factor for overland flow erosion	v__C_FACTOR.bsn	0.00	0.45
	USLE equation support practice factor	v__USLE_P.mgt	0.30	1.00
	USLE equation soil erodibility	r__USLE_K.sol	-0.20	0.20
	Peak rate adjustment factor for sediment routing in the subbasin	v__ADJ_PKR.bsn	0.50	2.00

a- r indicates a relative change (percentage) and v replaces the value of the parameter.
b- Only for forest.
c- These values varied for each land use.

3.3.2.1.1 Streamflow

Variations in the dynamic of sensitive parameters can be attributed to differences in dominant streamflow generation processes at different time scales for particular watersheds conditions. Therefore, the sensitivity of hydrological model parameters changed in different time scales and watersheds (Figure 2).

In agricultural watersheds (ANW and ASW), the most sensitive parameter in all time steps was SCS runoff curve number (CN2), followed by soil evaporation compensation factor (ESCO). Firstly, CN2, ESCO, LAT_TTIME (Lateral flow travel time), and RCHRG_DP (Deep aquifer percolation fraction) were the most sensitive parameters in the process of monthly streamflow simulation in both watersheds, added to GW_DELAY (Groundwater delay time) for ANW, and SOL_AWC (Available water capacity of the soil layer) and SOL_K (Saturated hydraulic conductivity) for ASW. Secondly, the sensitivity level of CN2, ESCO, GW_DELAY, LAT_TTIME and SOL_AWC in the process of daily streamflow simulation are the highest, followed by GWQMN (Threshold depth of water in the shallow aquifer required for return flow to occur) and SOL_BD (Moist bulk density) for ANW, and ALPHA_BF (Baseflow alpha factor) and SOL_K for ASW. Thirdly, CN2, SOL_BD and SOL_K are the most sensitive parameters in hourly streamflow simulation for both agricultural watersheds, followed by OV_N (Manning's value for overland flow) for ANW and ESCO, EPCO (Plant uptake compensation factor) and SOL_AWC for ASW.

In the Eucalyptus watershed (EW), the most sensitive parameters in every time step were CANMX (Maximum canopy storage), GW_DELAY and RCHRG_DP, followed by GWQMN and SOL_BD for monthly streamflow simulation, GWQMN, SLSOIL (Slope length for lateral subsurface flow) and LAT_TTIME for daily streamflow simulation, and LAT_TTIME, SLSUBBSN (Average slope length) and SOL_BD for hourly streamflow simulation.

In the grassland watershed (GW), the sensitive parameters varied in each time step. The most sensitive parameters to monthly streamflow simulation were ESCO, GW_DELAY, LAT_TTIME and SLSOIL. CN2 and RCHRG_DP were the most sensitive parameters for daily and hourly streamflow simulation, followed by ESCO, LAT_TTIME, RCHRG_DP, SOL_AWC and SOL_K for daily simulation, and GWQMN, OV_N and SURLAG (Surface runoff lag coefficient) for hourly simulation.

Overall, the most used parameters to streamflow calibration in every time step and watersheds were ALPHA_BF, CN2, ESCO, GW_DELAY, LAT_TTIME, RCHRG_DP and SOL_AWC.

3.3.2.1.2 Sediment yield

Eleven parameters were used for sediment yield calibration. Linear parameter for maximum amount of sediment re-entrained in channel sediment routing (SPCON) was the most used parameter in every time step and watersheds for sediment yield calibration.

The most sensitive parameters in agricultural (ANW and ASW) and grassland (GW) watersheds were RILL_MULT (Rill erosion coefficient), USLE_K (USLE equation soil erodibility), C_FACTOR (Scaling parameter for cover and management factor for overland flow erosion) and EROS_EXPO (Exponential coefficient for overland flow) which varied in each time steps. The USLE_K parameter was sensible in only monthly and daily SY simulation in ANW (Figure 2).

For the Eucalyptus watershed (EW), the sensitive parameters had greater variance in each time scale, only EROS_EXPO was sensible in every time-step. RILL_MULT, C_FACTOR, and EROS_EXPO were the most sensitive parameters for monthly sediment yield simulation. For daily SY simulation, SPCON and EROS_EXPO were the most sensitive. In hourly time scale, CH_COV1 (Channel erodibility factor), CH_COV2 (Channel cover factor), SPCON, C_FACTOR and EROS_EXPO were the most sensitive parameters for SSC simulation.

	Parameter	Monthly ANW	Monthly ASW	Monthly EW	Monthly GW	Daily ANW	Daily ASW	Daily EW	Daily GW	Hourly ANW	Hourly ASW	Hourly EW	Hourly GW
Streamflow	v__ALPHA_BF.gw	0.0	1.0	0.5	1.0	0.0	0.0	0.4	-	0.3	0.6	0.7	0.6
	r__BIOMIX.mgt	-	-	0.9	-	-	-	-	-	-	-	-	-
	v__CANMX.hru	-	-	0.0	-	-	-	0.0	-	-	-	0.0	-
	r__CH_K2.rte	-	0.5	-	-	0.6	-	-	-	-	-	-	-
	r__CH_N1.sub	-	-	-	-	-	-	-	-	1.0	-	-	-
	r__CH_N2.rte	-	0.5	-	-	0.7	-	-	-	0.9	-	-	-
	r__CN2.mgt	0.0	0.0	0.7	0.9	0.0	0.0	0.8	0.0	0.0	0.0	1.0	0.0
	v__EPCO.hru	-	0.6	-	-	-	-	0.2	0.8	-	0.0	-	-
	v__ESCO.hru	0.0	0.0	0.1	0.0	0.0	0.0	0.6	0.0		0.0	0.4	0.5
	v__GW_DELAY.gw	0.0	0.9	0.0	1.0	0.0	0.0	0.0	0.9	0.8	0.5	0.0	0.7
	v__GWQMN.gw	0.6	-	0.0	0.0	0.0	-	0.0	0.2	0.8	0.6	-	0.1
	v__GW_REVAP.gw	0.5	-	0.6	-	-	1.0	-	-	-	0.8	-	-
	r__HRU_SLP.hru	0.6	0.3	0.7	0.4	0.7	-	0.5	0.8	0.7	-	-	-
	v__LAT_TTIME.hru	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.7	-	0.0	0.6
	r__OV_N.hru	-	-	-	-	0.5	-	-	-	0.1	0.8	-	0.0
	v__RCHRG_DP	0.0	0.0	0.0	0.3	-	0.1	0.0	0.1	0.7	0.8	0.0	0.0
	r__SLSUBBSN.hru	0.0	0.1	0.2	0.3	-	-	0.3	-	0.3	0.3	0.0	-
	v__SLSOIL.hru	-	-	0.0	0.0	-	-	0.0	-	-	-	-	-
	r__SOL_AWC.sol	0.6	0.0	0.2	-	0.0	0.0	0.3	0.0	0.1	0.0	0.4	0.3
	r__SOL_BD.sol	-	-	0.0	0.4	0.0	0.0	-	0.5	0.0	0.0	0.0	-
	r__SOL_K.sol	0.2	0.0	0.9	0.9	0.3	-	-	0.0	0.0	0.1	0.9	0.3
	v__SURLAG.hru	-	-	-	-	-	-	-	-	0.4	0.3	0.6	0.1
Sediment yield / Suspended sediment concentration	v__CH_COV1.rte	-	0.1	0.5	0.2	0.7	0.9	0.9	0.5	-	0.7	0.0	0.7
	v__CH_COV2.rte	-	0.2	0.6	-	-	-	0.7	0.9	-	-	0.0	0.5
	v__PRF_BSN.bsn	-	-	0.6	0.5	0.6	-	0.8	-	-	-	0.1	-
	v__SPCON.bsn	0.6	0.5	0.4	0.4	0.4	0.2	0.0	0.5	0.3	0.3	0.0	0.1
	v__SPEXP.bsn	-	-	-	1.0	-	-	-	0.7	-	-	-	-
	v__EROS_EXPO.bsn	-	-	0.0	0.0	-	0.0	0.0	-	0.0	0.0	0.0	0.0
	v__RILL_MULTI.bsn	0.0	0.0	0.0	0.0	0.0	0.0	-	0.0	0.0	0.0	-	-
	v__C_FACTOR.bsn	-	0.0	0.0	0.0	-	0.0		0.0	-	0.0	0.0	0.0
	v__USLE_P.mgt	-	1.0	-	-	-	-	-	-	0.8	-	-	-
	r__USLE_K.sol	0.0	-	-	-	0.0	-	-	-	-	-	-	-
	v__ADJ_PKR.bsn	-	-	-	-	0.8	-	-	-	0.2	0.4	-	-

p-value: 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1

-: parameter did not use in calibration for this time interval.
p-value near zero is more sensitive.

Figure 2. Monthly, daily and hourly sensitivity analysis of SWAT model parameters for Agricultural North watershed (ANW), Agricultural South watershed (ASW), Eucalyptus watershed (EW), and Grassland watershed (GW).

3.3.2.2 Model performance

The evaluation metrics of streamflow and sediment yield at each watershed and different time scales of monthly, daily and hourly are shown in Table 4. During calibration and validation, we tried to ensure that the model performance was satisfactory according to criteria of Moriasi et al. (2007). Model simulation can be classified as satisfactory if NS > 0.50 at monthly time step, while $P_{bias} < \pm 25\%$ for streamflow and $P_{bias} < \pm 55\%$ for sediment yield. However, the criteria based on NS from Moriasi et al. (2007), could be applicable for R^2 because both statistics are based on squared differences between observed and simulated values (Krause et al., 2005).

The NS and R^2 of streamflow and sediment yield simulations in monthly and daily scales are all > 0.50, $P_{bias} < \pm 25\%$ for streamflow and $P_{bias} < \pm 36\%$ for sediment yield. These calibration and validation results demonstrated satisfactory performance, and the models reflect the hydrological and sedimentological processes in all four watersheds. Exceptions were NS and R^2 for simulated sediment yield in ASW at daily time step, which were 0.40 for both metrics on calibration, lower than the 0.50 threshold. However, Moriasi et al. (2007) criteria were recommended for model evaluation at monthly time step, in which the increase of temporal resolution of simulations, such as monthly time step to daily or hourly time step, often results in poorer model performance. The criteria for monthly evaluation can be relaxed slightly for daily and hourly time steps.

For hourly scale, streamflow simulation had better performance in Agricultural and Grassland watersheds (NS and $R^2 \geq 0.40$ and $P_{bias} \leq \pm 39\%$) than EW (NS and $R^2 \geq 0.30$ and $P_{bias} \leq \pm 26\%$). Therefore, suspended sediment concentration simulation at hourly time step was NS ranging from -0.2 to 0.2, R^2 ranging 0.0 to 0.4, and P_{bias} from 1.2% to 70.8%.

Simulated and observed monthly, daily and hourly streamflow and sediment yield are shown in Figures 3 to 5. In general, simulated streamflow in all time scales matched the observed data well. At all time scale, the model tended to underestimate high flows and overestimate low flows for both calibration and validation periods in the four watersheds.

The simulation results of monthly streamflow and sediment yield are poor in the flood period for all watersheds (Figure 3), e.g., on the highest SF and SY peaks, there is a large difference between observed and simulated values. In Agricultural watersheds (ANW and ASW), observed streamflow on October 2019 were 0.14 and 0.08 $m^3\ s^{-1}$, and simulated streamflow was 0.08 and 0.04 $m^3\ s^{-1}$ for ANW and ASW, respectively, a difference of 40%. In EW and GW, observed streamflow, on October 2015 and October 2019, were 0.03 and 0.09 m^3

s^{-1}, and simulated streamflow was 0.02 and 0.06 m^3 s^{-1} for EW and GW, respectively. Consequently, the same behavior could be observed in simulated SY in which the difference of observed and simulated SY ranged from 20% to 55% for ASW and EW, respectively.

Rise and recession of streamflow and sediment yield peaks in daily hydrographs and sedimentographs were well simulated in all watersheds (Figure 4), despite underestimation at high peaks (decrease from 50% to 78% in the highest streamflow peak, and from 30% to 70% in the highest sediment yield peak) and overestimation at many low peaks in daily events. The best daily simulation streamflow and sediment yield were in the GW (Figure 4d).

Therefore, daily baseflow simulation for EW and ASW was poor. An underestimation in EW and an under and overestimation in ASW could be observed, e.g., a decrease of 75% in baseflow simulation for EW (the observed baseflow on June 14, 2014, was 0.004 m^3 s^{-1}, and simulated streamflow was 0.001 m^3 s^{-1}) and an increase of 66% in ASW (the observed streamflow on June 26, 2017, was 0.012 m^3 s^{-1} and simulated baseflow was 0.035 m^3 s^{-1}). The baseflow alpha-factor (ALPHA_BF) was changed to improve simulation baseflow in calibration process, but the results of streamflow simulations were not improved.

Hourly simulated hydrographs were well represented (Figure 5). Hourly simulations could capture the timing of streamflow peaks, rises, and recessions. For most rainfall events, simulated peak streamflow was underestimated in all watersheds. The highest recorded streamflow peak for each watershed was underestimated at 45.3%, 60%, 76%, and 45.6% for ANW, ASW, EW, and GW, respectively.

Hourly simulation of suspended sediment concentration, in general, could not perform well. Despite the models could simulate some SSC peaks, this did not happen in all rainfall events and watersheds, mainly in EW and GW (indicated by the worst model's performance). Furthermore, hourly models underestimated suspended sediment concentration during calibration and validation periods in the four watersheds (indicated by the positive P_{bias} in Table 4).

Table 4. Monthly, daily and hourly statistical indicators obtained for calibration and validation of streamflow and sediment yield simulations for Agricultural North watershed (ANW), Agricultural South watershed (ASW), Eucalyptus watershed (EW), and Grassland watershed (GW).

Calibrated variable	Time scale	ANW			ASW			EW			GW		
		NS	R^2	PBIAS	NS	R^2	PBIAS	NS	R^2	PBIAS	NS	R^2	PBIAS
Calibration													
Streamflow	Monthly	0.7	0.7	16.6	0.6	0.6	12.6	0.6	0.6	15.1	0.7	0.7	-2.6
	Daily	0.5	0.5	-9.8	0.5	0.5	5.4	0.7	0.6	14.7	0.7	0.7	-11.3
	Hourly	0.6	0.6	1.5	0.4	0.4	26.1	0.3	0.3	25.4	0.5	0.5	-1.5
Sediment yield	Monthly	0.6	0.6	20.2	0.5	0.6	15.2	0.6	0.6	5.9	0.8	0.8	24.6
	Daily	0.5	0.5	35.6	0.4	0.4	22.3	0.6	0.5	14.9	0.6	0.6	-0.4
	Hourly	0.1	0.2	64.2	0.1	0.1	4.9	0.0	0.0	13.0	0.0	0.1	1.2
Validation													
Streamflow	Monthly	0.9	0.9	14.7	0.7	0.8	-12.1	0.6	0.6	-3.9	0.8	0.8	-3.6
	Daily	0.9	1.0	-24.4	0.6	0.7	-23.2	0.7	0.7	12.8	0.7	0.7	5.7
	Hourly	0.7	0.7	-18.9	0.4	0.5	-39.0	0.5	0.4	-3.4	0.3	0.4	4.0
Sediment yield	Monthly	0.9	1.0	16.9	0.5	0.6	5.8	0.7	0.7	2.4	0.5	0.6	-0.4
	Daily	0.9	0.9	3.3	0.4	0.4	30.6	0.5	0.5	-8.3	0.3	0.4	26.9
	Hourly	0.1	0.4	70.8	0.1	0.1	25.4	-0.2	0.1	1.8	0.2	0.0	25.5

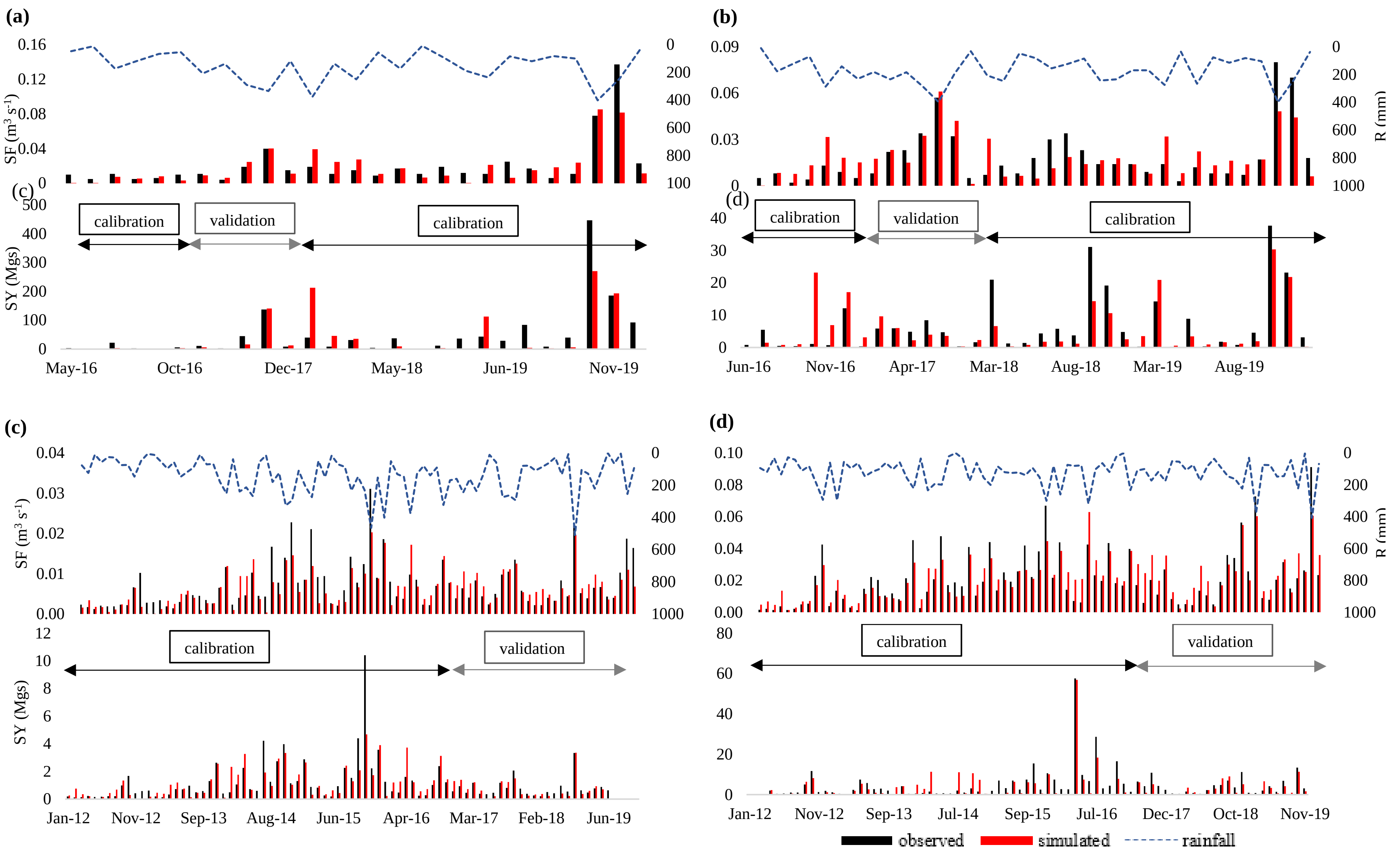
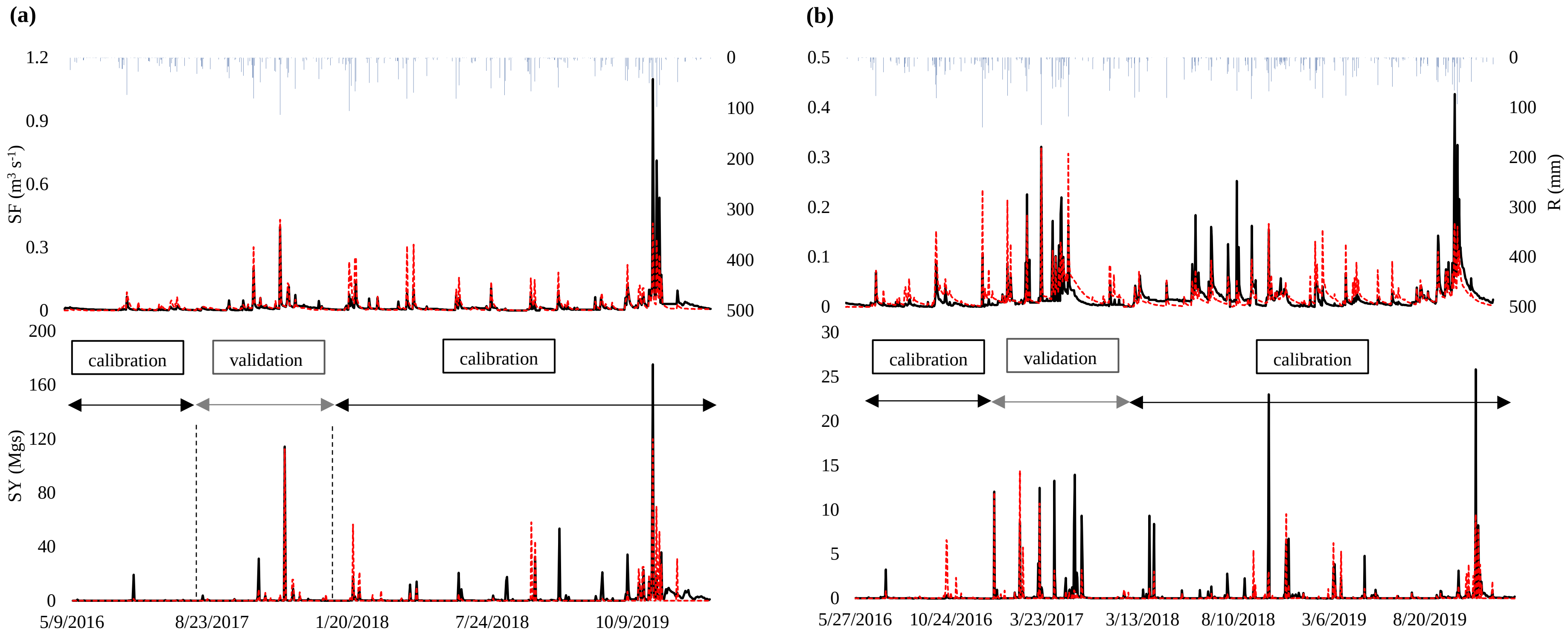


Figure 3. Monthly simulated and observed streamflow and sediment yield for (a) Agricultural North watershed (ANW), (b) Agricultural South watershed (ASW), (c) Eucalyptus watershed (EW), and (d) Grassland watershed (GW).


(a)
1.2
0.9
0.6
0.3
0
SF (m³ s⁻¹)
0
100
200
300
400
500
200
160
120
80
40
0
SY (Mgs)
calibration
validation
calibration
5/9/2016
8/23/2017
1/20/2018
7/24/2018
10/9/2019
(b)
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
400
500
R (mm)
30
25
20
15
10
5
0
calibration
validation
calibration
5/27/2016
10/24/2016
3/23/2017
3/13/2018
8/10/2018
3/6/2019
8/20/2019

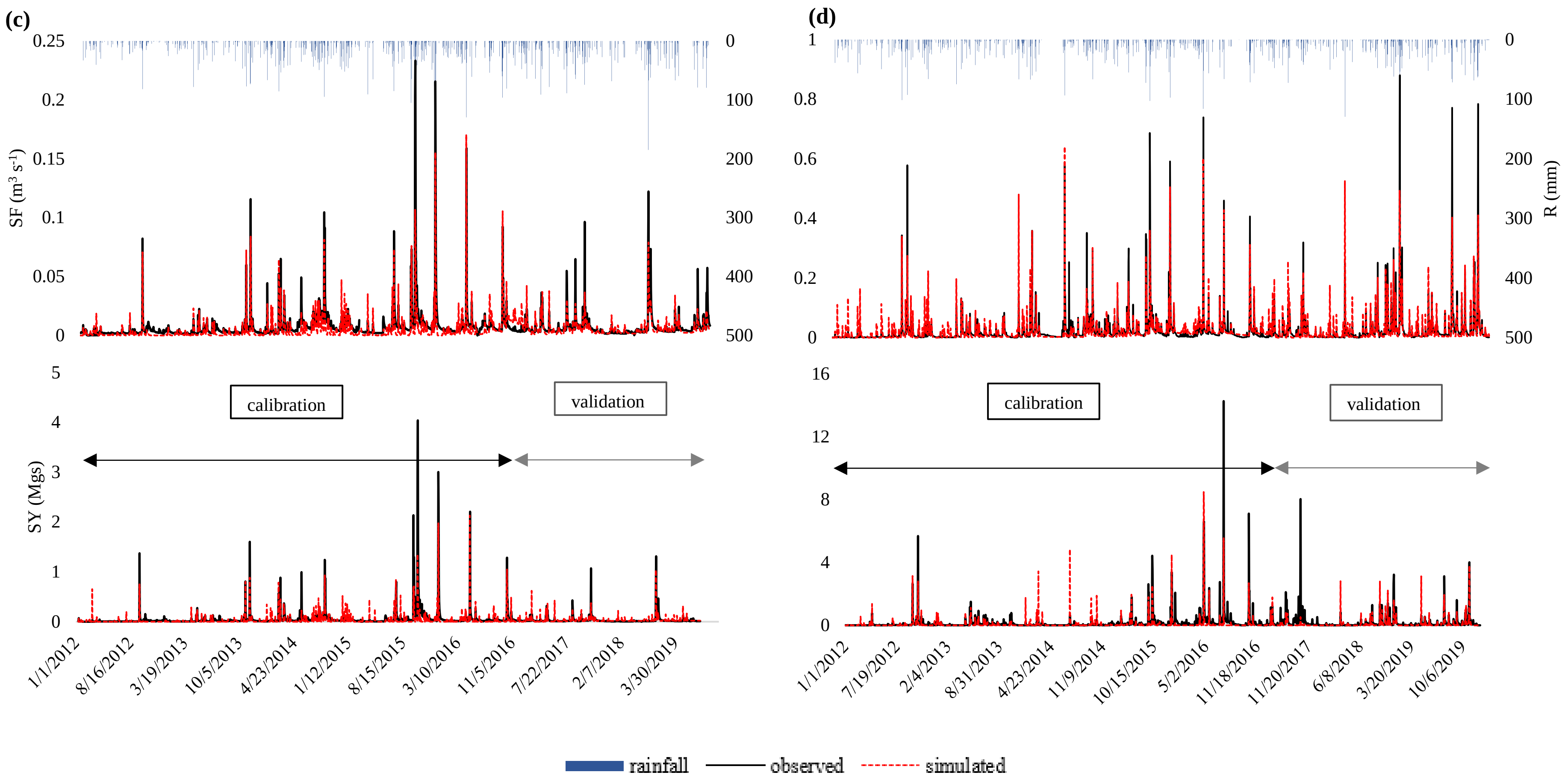
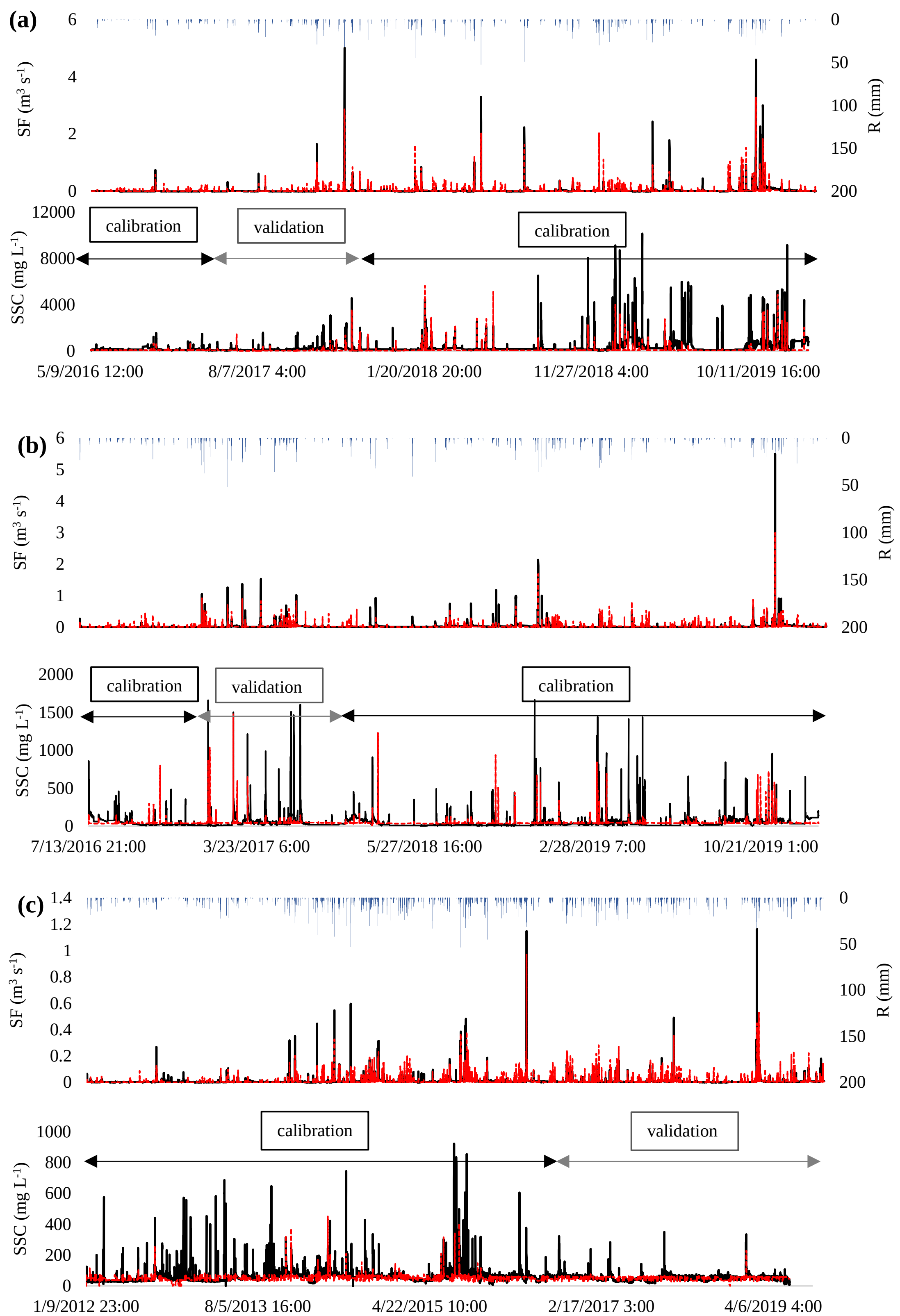


Figure 4. Daily simulated and observed streamflow and sediment yield for (a) Agricultural North watershed (ANW), (b) Agricultural South watershed (ASW), (c) Eucalyptus watershed (EW), and (d) Grassland watershed (GW).



(a)
SF (m3 s-1)
R (mm)
SSC (mg L-1)
calibration
validation
calibration
5/9/2016 12:00
8/7/2017 4:00
1/20/2018 20:00
11/27/2018 4:00
10/11/2019 16:00
(b)
SF (m3 s-1)
R (mm)
SSC (mg L-1)
calibration
validation
calibration
7/13/2016 21:00
3/23/2017 6:00
5/27/2018 16:00
2/28/2019 7:00
10/21/2019 1:00
(c)
SF (m3 s-1)
R (mm)
SSC (mg L-1)
calibration
validation
1/9/2012 23:00
8/5/2013 16:00
4/22/2015 10:00
2/17/2017 3:00
4/6/2019 4:00

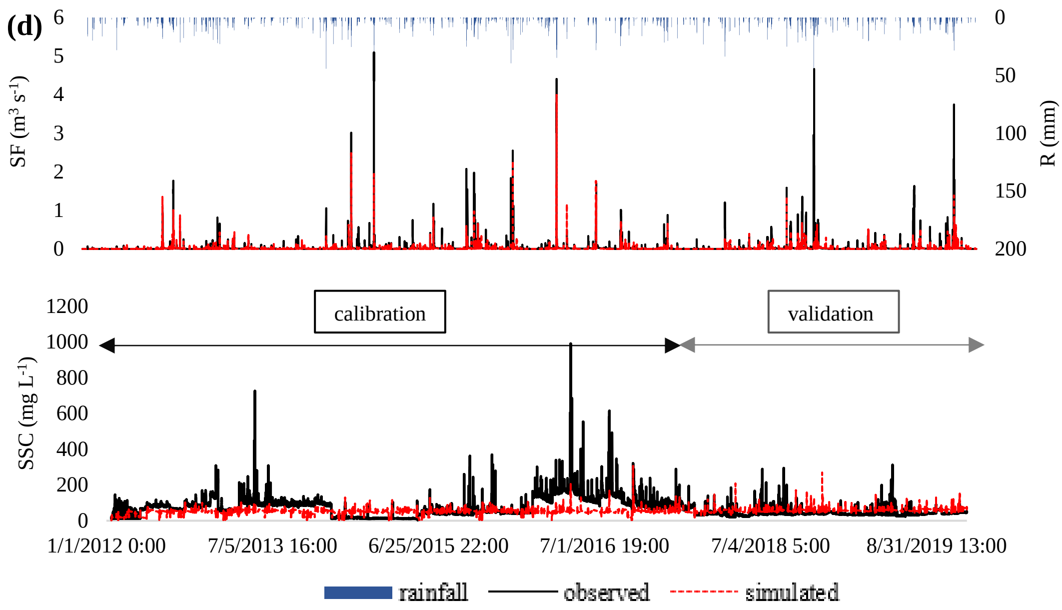


Figure 5. Hourly simulated and observed streamflow and sediment yield for (a) Agricultural North watershed (ANW), (b) Agricultural South watershed (ASW), (c) Eucalyptus watershed (EW), and (d) Grassland watershed (GW).

3.3.3 Hydrological and soil erosion temporal dynamics

Hydrographs and sedimentographs showed large intra-time scale variability governed primarily by the volume of rainfall (Figure 3 to 5). The year 2019 was characterized by rainfall events of great magnitude that generated high values of streamflow and sediment yield in the four studied watersheds, and also 2015 for EW and GW. ANW, ASW, and GW on October and November of 2019 presented the highest SF and SY values (except in GW, the highest SY was on April 2016). This was due to occurrence of wet period and an extreme event at ending of October 2019. For EW, the wet period was from September 2015 to December 2015 which presented high SY and SF values (Figure 3).

Rainfall effect on streamflow and sediment yield was more evident in ANW and ASW compared with the other watersheds. The highest SF and SY on the entire period were found in the following sequence: ASW>GW>ANW>EW and ANW>ASW>GW>EW, respectively. The largest recorded maximum streamflow and sediment yield were almost 70% and 90% higher in ASW and ANW than in EW, respectively. The highest sediment yield contribution from ANW was due to greater area, steeper slopes, higher proportion of cropland area, and less riparian vegetation which contributes to higher amount of sediment per unit of area.

Maximum monthly, daily and hourly rainfall in Eucalyptus watershed (510.17 mm, 184.95 mm, and 53.63 mm, respectively) were greater than in the three other watersheds (Figure 3 to 5). However, this watershed showed a lower streamflow and sediment yield compared to other watersheds. The recorded maximum streamflow in EW was 61.25%, 46%, and 78% lower than ASW on monthly, daily, and hourly time scales, respectively. Sediment yield was proportionally much lower, with almost 97% less than ANW for all time scales. Therefore, compared to Grassland paired watershed, the maximum streamflow was recorded on 01/09/2019 event in both watersheds, the GW streamflow was 75.1% higher than in the EW, and sediment yield was five times greater in GW (Figure 5c and 5d).

Mean streamflow in ASW is larger than in the three other watersheds. The highest recorded streamflow (10/30/2019) in ASW showed 13% higher than in the ANW (Figure 4a and 4b). However, the maximum recorded sediment yield in ANW showed an SSC peak almost seven times greater than ASW (Figure 5a and 5b).

Important features of extreme rainfall events are not evident on a monthly and daily scale. For example, a 5-day event that occurred on October 2019 in ANW and ASW with rainfall ~160 mm generated more than 70% of sediment yield for that month. Another example was in EW, on October 2015, where a 6-day event represented more than 75% of sediment yield for that month. The same occurs on an hourly time scale, which is not evident at a daily scale. For example, an 8 hours event that occurred on 04/25/2016, in GW with rainfall ~167 mm generated more than 80% of suspended sediment concentration for that day.

In the four watersheds, the variability is partly controlled by volume of rainfall, erosion and, mainly, land use in the watershed. In general, high correlation between rainfall and streamflow can be observed on every time scale (Table 5). The best correlation between hydrossedimentological variables was found on monthly scale for ANW and ASW (from 0.59 to 0.9) and on daily scale for EW and GW (from 0.68 to 0.94). However, streamflow exhibited a flashy response to rainfall events at all four watersheds, with runoff peaks represented well in hourly hydrographs (Figure 5), and high correlation between rainfall and streamflow at hourly time scale (0.61 to 0.69). The best representation of sediment yield was on monthly and daily time scales, with the highest correlation was found between streamflow and sediment yield on daily scale (from 0.71 to 0.96) (Table 5). On short-term, the SSC does not depend only on rainfall but also on several other factors, such as antecedent soil moisture, surface runoff, sediment transport, and deposition processes.

Table 5. Pearson Correlation between rainfall (R), streamflow (SF), sediment yield (SY) and suspended sediment concentration (SSC) for Agricultural North watershed (ANW), Agricultural South watershed (ASW), Eucalyptus watershed (EW), and Grassland watershed (GW) in each time scale.

Pearson Correlation					
Time scale	Related variables	ANW	ASW	EW	GW
Monthly	R x SF	0.76	0.86	0.94	0.77
	R x SY	0.78	0.7	0.92	0.68
	SF x SY	0.9	0.59	0.91	0.72
Daily	R x SF	0.74	0.77	0.81	0.86
	R x SY	0.54	0.66	0.87	0.8
	SF x SY	0.71	0.71	0.96	0.93
Hourly	R x SF	0.68	0.61	0.69	0.61
	R x SSC	0.46	0.39	0.12	0.29
	SF x SSC	0.69	0.58	0.27	0.38

3.4. DISCUSSION

3.4.1 Sensitivity analysis and model performance evaluation

The success of calibration models depends on the parameterization of soil, climate, and land use input data and the sensitivity analysis and calibration of models (Abbaspour et al., 2015; Arnold et al., 2012). Sensitivity analysis can be used to identify the model parameters that have an impact on simulations (Abbaspour et al., 2018; Arnold et al., 2012) and to understand mechanistic relationships of controlling hydrological and soil erosion processes (Abbaspour et al., 2007, 2018; Guse et al., 2019).

We could observe that the sensitivity of parameters is related to different characteristics of watersheds (mainly land use) and the model time-scale. Agricultural and grassland watersheds models (ANW, ASW and GW) proved to be highly sensitive to parameters of runoff (CN2 and ESCO) to streamflow calibration in all time steps. These parameters are some of the most used and sensitive for streamflow simulation in several studies (Abbaspour et al., 2015; Bressiani et al., 2015b, 2016; Busico et al., 2020; Lopes et al., 2020; Osei et al., 2021). CN2 has the primary influence on the amount of runoff generated from each HRU (Serrão et al., 2021; Singh & Jha, 2021); this parameter has a great impact on watersheds with different land uses and soils. The ESCO controls the contribution of soil water from deeper zones to the evaporation process and depends mainly on soil texture (Guse et al., 2019; Serrão et al., 2021). Soil texture has a significant influence on soil water, where more than 60% of ANW and ASW areas are composed of Ferralsols and Nitisols that are soils with a large percentage of clay (~50%). These soils can retain water strongly (Reichert et al., 2009, 2020; Vaz et al., 2005) and can also reach the evaporative zone due to the movement of water in soil through capillarity (Brady & Weil, 2009).

For planted Eucalyptus watershed (EW), runoff and underground flow parameters (CANMX, GW_DELAY, RCHRG_DP) were more sensible to calibrate streamflow at all time steps. The CANMX depicts the water capacity of the canopy storage and depends on the leaf area index (LAI), which affects mainly planted forest watersheds (Cecílio et al., 2019; Marin et al., 2020; Meaurio et al., 2015; Oliveira et al., 2020). Underground and percolation flow parameters, GW_DELAY and RCHRG_DP, depend on soil and bedrocks types. Soil in EW are characterized to have a large percentage of sand (~60%) that promotes percolation of water and underground processes, as also reported by Marin et al. (2020), Serpa et al. (2015) and Serrão et al. (2021).

The parameters for calibrating sediment yield are divided into parameters that control channel processes and control overland processes (Boithias et al., 2017; Me et al., 2015). Parameters that control overland processes (RILL_MULT, C_FACTOR, EROS_EXPO) were the most sensitive for all watersheds to simulate sediment yield. However, the channel parameters (CH_COV1 and CH_COV2) were sensitive in the EW and GW calibrations in which the channel of these watersheds is the most source of sediments (Valente et al., 2020).

The temporal parameters sensitivity analysis in the four watersheds shows that the relevance of model parameters varies between watersheds. Although there is not the same behavior about the sensitive parameters in each time scale for all watersheds, there is a tendency of underground (GW_DELAY and GWQMN) and percolation parameters (RCHRG_DP and LAT_TTIME) being more expressive on a monthly and daily scale, while soil parameters (SOL_BD and SOL_K) are more expressive at hourly time scale. Wu et al. (2020) also showed that GW_DELAY and RCHRG_DP were more sensitive parameters in daily streamflow simulation process than in other time scales. The same was found in Guse et al. (2019), where GW_DELAY and LAT_TTIME were the most sensitive groundwater and lateral flow parameters for all months in different German catchments. Bressiani (2016) also found GW_DELAY was the most sensitive parameter on monthly calibration.

According to Jeong et al. (2010), the sensitivity of SWAT parameters was significantly influenced by the model time step. Parameters related to channel routing are more influential in a higher resolution time (less than one hour), and groundwater flow parameters get more influence in a lower resolution time, such as monthly and daily. Boithias et al. (2017) found RCHRG_DP and GWQMN as the most sensitive parameters for a 15 km^2 watershed on the daily scale, and parameters related to channel routing (CN_N2 and CH_K2) were more sensible at hourly time step. This study found soil parameters as the most sensitive on the hourly scale (SOL_BD and SOL_K), which directly influence surface runoff generation and, therefore, the flow peaks of hydrographs.

The models adequately simulated streamflow in all time scales and watersheds, based on criteria for model performance established by Moriasi et al. (2007). Bressiani (2016) and Wu et al. (2020) also showed a satisfactory streamflow model in different time scales (annual, monthly, and daily). Therefore, the models' performance tends to be better on higher time scales, such as on a monthly scale than on a daily scale (Duguma et al., 2020; Lopes et al., 2021; Yonaba et al., 2021). This occurs due the performances conducted on monthly measurements tend to smooth out the predicted error by reducing the peaks and rises in the data (Moriasi et al., 2007).

Sediment yield simulations showed better performance on monthly and daily than on hourly scale. According to Sith and Nadaoka (2017), the simulation of suspended sediment concentration (SSC) is more difficult than sediment yield simulation. Although the developed sub-daily algorithm can predict SSC in a small watershed (Jeong et al., 2010), SWAT still does not consider the overland flow transport and sediment deposition from previous flood events.

3.4.2 Hydrological and soil erosion responses to different time scales

Hydrographs and sedimentographs showed that the hydrological and soil erosion responses varied in each time scale at the four watersheds (Figure 3 to 5). In each time scale, different processes control hydrological and soil erosion behavior (Baffaut et al., 2015; Guse et al., 2019; Lane et al., 1997). For example, at the event scale (minutes to hours), runoff could be controlled by the characteristics of rainfall and the watershed. At a long-term scale, runoff is dominated by geomorphological processes, climate variability, anthropogenic effects, and variability in precipitation (Blöschl and Sivaplan, 1995). Besides, several factors can interfere in production of runoff and sediment yield, such as rainfall patterns, roughness, topography, soil cover and soil properties. Some studies claim that characteristics of intensity, duration, and erosivity of rainfall were the dominant factors to affect surface runoff and sediment yield in short run (Alavinia et al., 2019; de Almeida et al., 2021; Fang et al., 2012; Zheng et al., 2021).

Furthermore, rainfall impact on hydrological processes at small scales (areas less than 1 km^2) could be more expressive than at large scales (Baffaut et al., 2015), because of the rapid hydrological response in small scales. In our study, Pearson correlation coefficient demonstrated that rainfall is the most relevant (high correlation) variable to control streamflow at all time scales. There are significant positive correlations between monthly, daily, and hourly streamflow and rainfall in all watersheds, with correlation coefficients from 0.61 to 0.94 (Table 6). This indicates that streamflow processes of the four watersheds are highly consistent with the rainfall changes in three different time scales. The same was found by Wu et al. (2020), where rainfall was the most relevant meteorological factor to runoff at various time scales compared to other meteorological factors, e.g., evaporation and temperature.

The magnitude of hydrological and soil erosion processes depends on the temporal scale (Baffaut et al., 2015; Gentine et al., 2012). The smallest time scales, such as hourly and daily, can detect different hydrological and erosion processes, e.g., infiltration, evapotranspiration, runoff, sediment detachment, and others (Baffaut et al., 2015). However, increased time scale detects slower land-surface processes, such as groundwater processes, which might be loosely constrained by short-term observations (Gentine et al., 2012). Thereby, flow peaks in hourly and daily hydrographs were better detected than in monthly hydrographs (Jeong et al., 2010; Li et al., 2018; Yang et al., 2016). In contrast, peaks of sediment yield were better represented in daily sedimentographs, as also found by Meaurio et al. (2021). Some soil erosion processes, such as deposition and transport sediment from antecedent rainfall events, cannot be captured on a small-time scale (Merrit et al., 2003).

Overall, large variability in sensitive parameters was observed which can be attributed to differences in the dominant water and sediment yield mechanisms at different time scales for each watershed (Coron et al., 2012; Wu et al., 2020). Recent studies have shown high temporal variability in the sensibility of parameters and between different watersheds (Guse et al., 2016; Guse et al., 2019; Reusser et al., 2011; Singh and Jha, 2021). Different values of monthly, daily, and hourly calibrated parameters were attributed at each time step (Table 3). Thereby, hydrographs and sedimentographs simulated by monthly, daily, and hourly calibrated models had substantial differences. Because of this, it is important to calibrate the model for a specific time scale according to aim of the study. Adla et al. (2019) suggested that the models calibrated on monthly data produced unrealistic simulations of daily streamflow because the monthly calibrated model could capture only monthly streamflow patterns and it did not reliably represent daily rainfall-runoff. In addition, the definition of time scale for model calibration is necessary (Abbaspour et al., 2018) due to time scale for the calibrated model to evaluate climate change or land-use change is different than to evaluate flooding processes (Bai et al., 2021).

3.4.3 Hydrological and soil erosion responses to the different land uses

This study confirms that land use is a major factor for hydrological and soil erosion processes, as suggested previously (Ni et al., 2021; Sidibe et al., 2019; Yonaba et al., 2021). The hydrographs and sedimentographs showed that the highest streamflow and sediment yield were attributed to Agricultural and Grassland watersheds compared to Eucalyptus watershed. Cropland and grassland land use have less protected soil, smaller interception, and higher soil management (e.g., tillage and livestock) than forest land use. Forests have a large canopy, great leaf area, and more protection of soil surface by litter layer compared to other land uses, promoting an increase of rainfall interception, evapotranspiration, and soil infiltration and, consequently, reducing surface runoff and sediment yield (Ebling et al., 2021a; Hu et al., 2021; Valente et al., 2021).

Previous studies about conversion land use indicate that land use change has high effects on future surface runoff and sediment yield. Hu et al. (2021) investigated the impact of land use changes on water cycle in a Loess Plateau watershed under cropland, forest, and grassland, and found less water yield in conversion cropland to forest due the forests can capture more rainfall, uptake more water and higher evapotranspiration than cropland. The opposite was investigated by Lopes et al. (2021), in which the conversion from forest to cropland and grassland increased surface runoff due to decrease interception and infiltration rates. Serrão et al. (2021) also studied the impact of land use change, and observed that subbasins with grassland were more susceptible to increased surface runoff and sediment yield.

Hydrology affected by conversion from grassland to planted forest should be investigated with a focus not only on streamflow (blue water) but also on variables that optimize water management such as soil moisture (green water) (Falkenmark & Rockström, 2004). Thereby, many studies suggested that planted forest expansion could reduce surface runoff and increase evapotranspiration and soil moisture through improving soil structure, and thus water infiltration and water productivity (Falkenmark and Rockström, 2010; Ferreto et al., 2021; Li et al., 2020; Li et al., 2021; Suzuki et al., 2012, 2014; Valente et al., 2021).

About the Agricultural paired watersheds, both are similar in terms of land use but differ in size of drainage area, riparian vegetation, and soil properties. The Agricultural North watershed (ANW) showed more susceptibility to soil erosion than Agricultural South watershed

(ASW). The presence of riparian vegetation in ASW provided less soil erosion due to riparian vegetation contains sediments transferred from cropland to water body, acting as a physical filter (Ebling et al., 2021b; Sirabahenda et al., 2020; Tiecher et al., 2017; Waidler et al., 2011). Furthermore, the drainage area of ANW is almost two times bigger than ASW, which contributes to a higher amount of sediment per unit of area (Didoné et al., 2014). Despite there being similar soil classes in both watersheds, some soil properties are different; for instance, ANW showed deeper soils and higher saturated hydraulic conductivity than ASW's soils. These properties positively affect hydrological behavior, resulting in lower surface runoff in ANW compared to ASW (Ebling et al., 2021b). Bouslihim et al. (2019) investigated soil properties that affect hydrological components, and found soil depth and hydraulic properties are the main factors responsible for surface runoff.

Although croplands of agricultural watersheds were under no-till, we could observe high sediment yield in both watersheds, mainly in ANW. Some studies emphasized that only no-till adoption in cropland is not enough to control soil erosion processes (Didoné et al., 2014, 2015, 2021; Londero et al., 2018). In two paired zero-order catchments under no-till cultivation with and without broad-based retention terraces, Londero et al. (2018) observed that no-till without terraces was unable to adequately control surface runoff and soil erosion. However, when both practices were adopted, runoff and soil erosion was better controlled. According to Merten et al. (2015) and Ali et al. (2016), mechanical practices are more efficient to control surface runoff and reduce soil erosion.

The findings of this study will contribute to helping modelers to calibrate hydrological models. Firstly, the outcomes showed different hydrological and soil erosion behavior in distinct land uses and time scales. Defining the time scale to model calibration showed essential because the processes that each time step represents are different. Lastly, we could observe that the sensitivity analysis of parameters was influenced by watershed characteristics such as land use and the time scale.

3.4.4 Limitations and future researches

This study is subjected to some limitations that can be resolved in future works. Firstly, there are some periods of missing measured data in all watersheds due to datalogger and instruments failure in the monitoring section, and some errors could be detected in measured data, mainly in turbidimeters. Sometimes, high turbidity was detected in drought periods which could be associated with a measured error. On the other hand, the short-term monitoring in Agricultural watersheds could be another limitation, becoming important to continue the hydrological and sedimentological monitoring in these watersheds to capture long-term responses of land use changes.

Secondly, input data of soils parameters were collected by Ebling (2016) and Morales (2013). These parameters were evaluated in the most representative soil profile in each soil class. However, soil parameters have great spatial variability that is important to increase the number of evaluated soil samples in each soil class and land use. For this, pedotransfer functions (PTFs) have been used as viable options to estimate soil parameters needed for hydrological modeling (Wösten et al., 2001). However, high resolution of input soil data will improve the hydrological and sedimentological modeling (Krpec et al., 2020).

Thirdly, internal equations to estimate surface runoff and sediment yield in the SWAT model could bias the simulations. The Green-Ampt method showed overestimation in some events to simulate sub-daily surface runoff, previous studies also observed this (Bauwe et al., 2016; King et al., 1999; Meaurio et al., 2021). This method represents the HorMgian mechanism of surface runoff (SR) generation, which considers SR generation when the rainfall intensity is greater than infiltration capacity, without accounting flood areas or contributions from other sources areas. Furthermore, the sub-daily SSC simulation did not represent well, which the sub-daily routine of soil erosion, sediment transport, and deposition could be improved. In general, there is more uncertainty on sub-daily simulations, which needs increasing the input information to better modeling.

Despite these limitations, the methodology and input data used in this study support our conclusions. Nonetheless, addressing these limitations by evaluating long-term land use and climate change and testing other models (e.g., SWAT+) in these watersheds can be a good subject of future studies.

3.5 CONCLUSIONS

In this study, we investigated the temporal dynamics of hydrological and soil erosion processes in four watersheds under the three main economic land uses (cropland, grassland, and planted forest). The watershed characteristics analysis showed that land use activities were a major factor to streamflow and sediment yield responses. Eucalyptus watershed (EW) showed the lowest streamflow and sediment yield. The highest streamflow and sediment yield was found in Agricultural South watershed (ASW) and Agricultural North watershed (ANW), respectively.

The SWAT model performed satisfactorily to simulate streamflow and sediment yield in all time scales, except on hourly suspended sediment concentration (SSC) simulations. The most sensitive parameters varied with time scale and watershed. Parameters that represent slower processes such as groundwater flow were more sensible in higher time scales (monthly and daily) than in lower time scales (hourly). On the other hand, parameters that directly influence surface runoff generation, such as soil parameters, were more sensitive on the hourly time scales. Hence, defining the time scale of model calibration is important to understanding specific hydrological and soil erosion processes. Agricultural and grassland watersheds (ANW, ASW, and GW) proved higher sensibility to runoff parameters (CN2 and ESCO) than in the EW.

Differences in the correlation between hydrossedimentological variables at each time scale were identified. Streamflow at all time scales presented a highly-significant positive correlation with rainfall in the four watersheds, and sediment yield showed higher positive correlation with streamflow than rainfall. In summary, this study promoted a deeper understanding of the impact of land use activities on hydrological and soil erosion processes and the temporal dynamics in different conditions. Furthermore, findings from this study can provide valuable information for optimization of land use planning and the selective allocation of the best management practices (BMPs) in the four watersheds.

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4 ARTIGO 2 – DIFFERENT BEST MANAGEMENT PRACTICES APPROACHES TO REDUCE SOIL EROSION AND OPTIMIZE WATER BALANCE COMPONENTS IN WATERSHEDS UNDER GRAIN AND DAIRY PRODUCTION

(Artigo elaborado de acordo com as normas da revista *International Soil and Water Conservation Research*)

Abstract

Soil erosion and sedimentation are among the most serious global environmental problems. Soil and water conservation measures have been proven to be effective ways to reduce soil loss, in which they differ in their functionality in controlling erosive processes. The objective of this study was to evaluate the impact of the three approaches of soil and water conservation measures (soil management, vegetative measures, and mechanical methods) in two paired agricultural watersheds located in the plateau region of southern Brazil. Monitoring from 2016 to 2019 was carried out in two small paired agricultural watersheds (~1 km^2) called Northern (NRW) and Southern (SRW) watersheds. Modeling using SWAT was performed to simulate individual and combined best management practices (BMPs) by including the three approaches. Among the nine individual BMPs, the most effective was crop rotation and cover crop for both watersheds (SY reduction of 38.4 and 28.8% for NRW and SRW), followed by contouring farming for NRW (reduction of 27.6%) and terracing for SRW (reduction of 13.9%). Among the three conservation measures approaches, vegetative scenario was the most effective to reduce soil erosion (SY reduction of 43.5 and 34.1% for NRW and SRW). However, the association of all conservation approaches resulted in the highest reduction of soil loss at watershed (SY reduction of 46 and 41.5% for NRW and SRW) and sub-watershed (reduction from 40 to 50% in critical sub-watersheds) scales. All combined scenarios could optimize water balance components, such as surface runoff, baseflow, percolation, and total aquifer recharge. This study demonstrates that soil losses remain unsustainable in agricultural watersheds and there is misleading information provided to farmers about the efficiency of soil and water conservation measures. The findings of this study can help farmers to choose appropriate BMPs to reduce current soil erosion problems.

Keywords: soil management, vegetative measures, mechanical methods, SWAT.

4.1 INTRODUCTION

Soil erosion is one of the most serious global environmental problems. According to FAO (2019), accelerated soil erosion by overgrazing, intensive agriculture, and deforestation can increase soil loss by up to a thousand times. During the mid-1990s, about 30% of the world's cultivated land has become unproductive (Pimentel, 2006). However, if nothing is done to minimize soil erosion, over 90% of the world's cultivated land could become degraded in 2050 (FAO, 2019). The soil loss rate has been increasing mainly in South America, Southeast Asia, and Sub-Saharan Africa, where there is intense agriculture (Borrelli et al., 2017). Compared to countries of South America, the effects of soil erosion are severe in Brazil. Besides intense agriculture, Brazil has excessive soil erosion rates due to the rainfall regime, soil properties, and slope characteristics (Guerra et al., 2014). Therefore, Brazil could be considered a pioneer in the adoption of soil conservation practices (Landers, 2005).

In the late 1970s, the United Nations Food and Agriculture (FAO) and Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) started a soil conservation project in two representative watersheds from Plateau region of southern Brazil. This region has a particular characteristic related to highly-weathered soils, high rainfall erosivity (Oliveira et al., 2013), and intense agriculture, which contribute to severe soil erosion. The focus of the project was to promote conservation agriculture to minimize the sedimentation in reservoir Passo Real. However, the project was abandoned, and four decades later, the monitoring returned with a new context that included the modeling approach. Modeling approach has been widely used in soil erosion studies because it is an alternative tool that provides the effect of best management practices (BMPs) before the implementation at a watershed scale (Briak et al., 2019; Didoné et al., 2017; Strauch et al., 2013; Uniyal et al., 2020).

Studies focused on soil and water conservation measures have been carried out across the world (Afroz et al., 2021; Berihun et al., 2020; Briak et al., 2019; Didoné et al., 2017; Gashaw et al., 2021; Ricci et al., 2020; Strauch et al., 2013). The knowledge of the effect of soil and water conservation practices provides essential information to adequate management of land use. Conservation practices are broadly divided into soil management, vegetative measures, and mechanical methods (BerMgi and Lombardi Neto, 2014) that are implemented to improve soil infiltration rate, decrease the impact of raindrops and decrease velocity and volume of surface runoff, respectively. Uniyal et al. (2020) evaluated the effect of vegetative and mechanical practices in an Indian catchment and showed that mechanical BMPs were more effective in reducing sediment yields than vegetative BMPs. The same was found by Gashaw et al. (2021), in which the association of two mechanical methods (soil bunds and grassed waterways) provided a sediment yield reduction of 34% from the baseline scenario. Conversely, Laufer et al. (2016) implemented only vegetative measures and could reduce 98% of soil loss compared to base conditions of intense tillage. Himanshu et al. (2019) observed reduced sediment yield to 9% about conventional tillage by implementing different soil management, such as conservation tillage, zero tillage, and field cultivation.

Although the no-till is implemented to reduce soil erosion, the effectiveness of this practice is low, mainly in high rainfall. When this system is associated with a mechanical method, such as terraces, no-till has been shown efficient to decrease sediment yield (Londero et al., 2018). Yet, the association of these three conservation measures can provide better results to minimize soil erosion. For example, Didoné et al. (2017) evaluated the impact of different BMPs on soil erosion in an agricultural catchment under no-till and the most effective scenario included all types of conservation measures (crop rotation, contouring farming, terracing, and riparian forest). Therefore, limited studies have evaluated the impact of the three conservation measures approaches separately.

In southern Brazil, farmers have been implementing no-till alone rather than conservation agriculture (Reicosky, 2015). However, severe soil erosion and sedimentation problems have been occurred in the plateau region of southern Brazil, mainly in watersheds from Passo Real reservoir (Broetto et al., 2017; Ebling, 2018). To minimize soil erosion and its consequence problems, the association with other conservation measures, soil, vegetative and mechanical BMPs may improve soil properties, decrease surface runoff and sediment yield, thus reducing reservoir sedimentation. In general, understanding the impact of the different conservation measures on these representative agricultural watersheds is a key to helping farmers and decision-makers in choosing feasible and appropriate BMPs to reduce soil erosion problems on- and off-site.

Thereby, this study evaluated the effectiveness of different conservation measures approaches in two agricultural paired watersheds. We hypothesized that the implementation of each conservation approach (soil management, vegetative measures, and mechanical methods) separately is effective to reduce soil erosion. This study was carried out with the following objectives: (i) to quantify water and sediment yield in agricultural paired watersheds and identify critical sub-watersheds under current management by using SWAT model; (ii) to assess the effectiveness of individual and combined BMPs for controlling soil erosion based on the different BMPs approaches; and (iii) to simulate the effects of combined BMPs on water balance components.

4.2 MATERIAL AND METHODS

4.2.1 Study area

The study was conducted in two paired watersheds located in the physiographic plateau region in southern Brazil (state of Rio Grande do Sul). The watersheds drain directly into the artificial water reservoir Passo Real, one of the largest in Brazil, with over 225 km^2 in area (Figure 1). The reservoir Passo Real composes a system of energy generation with a power of 158 MW. These paired watersheds were chosen because they are representative for this region. The watersheds are dominated by grain and dairy production, and to characterize the magnitude of soil erosion and hydrological processes in similar conditions in terms of land use, soil, and climate, which differ in size, percentage of cropland areas, and riparian vegetation (Figure 1). Based on spatial position, one is called Northern watershed (NRW) (28°45'17.73"S and 53°6'11.12" W) and the other Southern watershed (SRW) (28°45'34.27" S and 53°6'28.83" W). The drainage area of NRW and SRW is 0.94 km^2 and 0.54 km^2, respectively.

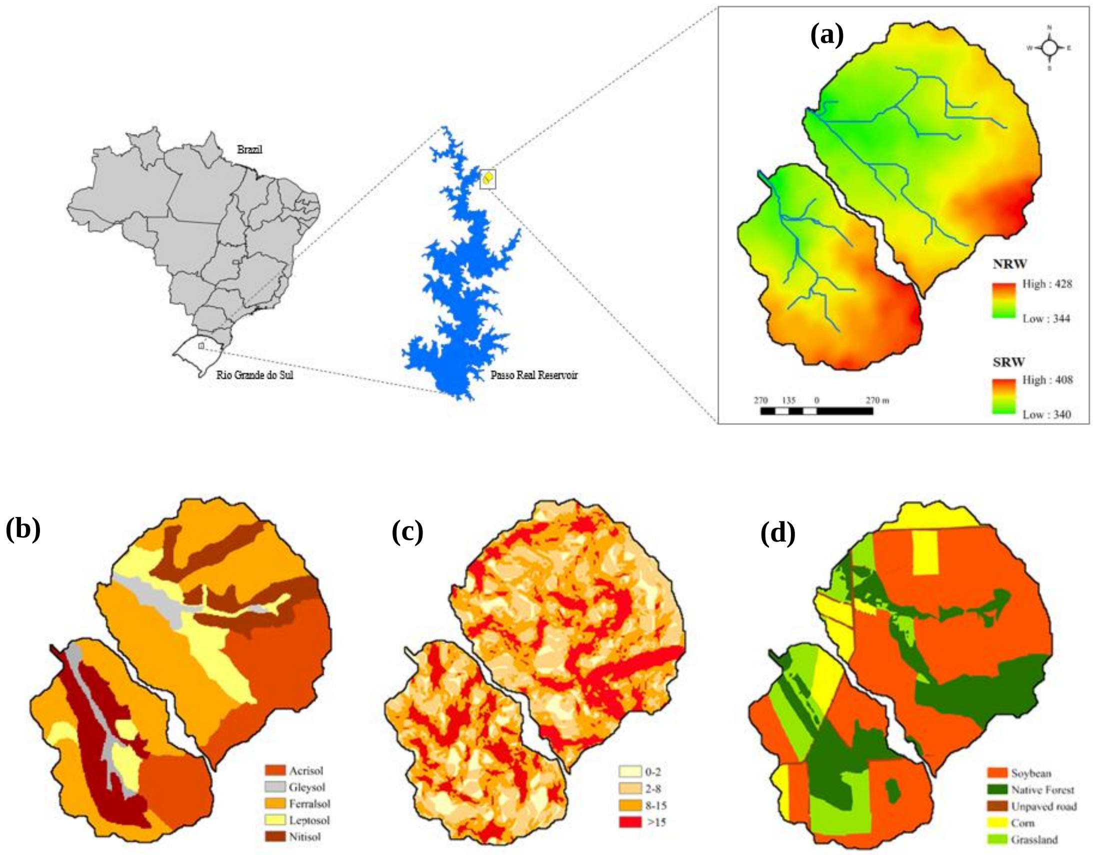


Figure 1. Location of the Northern (NRW) and Southern (SRW) watersheds and their maps of (a) elevation, (b) soil, (c) slope, and (d) land use. Source: ASF Data Search (2019) and Tornquist (2007).

According to Köppen, the climate is Cfa type, i.e., subtropical humid without dry season, with an average annual rainfall of 1,750 mm and an average temperature of 18 ºC (Alvares et al., 2013). The geological bedrock is basaltic, with deep and highly weathered soils (Ferrasols and Nitisols). The soils were classified according to the World Reference Base (WRB/FAO, 1998) as Ferrasols, Leptosols, Nitisols, Acrisols, and Eutric Gleysols (Figure 1b). The landscape includes gentle slopes (<8%) and hillside slopes with higher steepness (>15%) (Figure 1c). Land use in both watersheds consists of native forest, cropland, and cultivated pasture. The main crops in agricultural areas are soybean (*Glycine max*) and maize (*Zea mays*), and in cultivated pasture area consists of TifMg 85 (*Cynodon dactylon*) (Figure 1d).

These paired watersheds are dominated by the family farming system. It is characterized by small production areas under intensive grain cultivation under no-till. The no-till system in these areas only keeps the ground cover from previous crops.

4.2.2 Hydrological and soil erosion monitoring

Watersheds were monitored for four years, from April 2016 to December 2019. Rainfall (R), water yield (WY), and sediment yield (SY) were measured using automatic sensors recorded at 10-min intervals. Each automated measuring station consisted of a spillway located in a watershed outlet with a rainfall gauge, a water level sensor (limnigraph), and a turbidity sensor (turbidimeters) connected to a data logger. The WY was estimated from water level measurements by the conversion of pressure values into the flow using the appropriate discharge rating curve calculated for the monitoring section (EMBRAPA Trigo). Suspended sediment concentration (SSC) was determined using a turbidimeter that automatically measured water turbidity by scattering of light. Turbidity values were converted into NTU, and the NTU was converted into SSC using a calibration curve obtained by manually collecting samples during rainfall events (Ebling, 2018). Finally, SY was estimated by multiplying WY and SSC.

4.2.3 Modeling hydrological and soil erosion processes

4.2.3.1 Model setup

Hydrological and soil erosion processes were simulated using Soil and Water Assessment Tool (SWAT) model. SWAT is a process-based, semi-distributed, and continuous-time model (Arnold et al., 1998). It was developed to predict the impact of management practices on water, sediment, and agricultural chemical at a watershed scale. SWAT model requires a large amount of spatial (i.e., DEM, land use, and soil maps) and temporal (meteorological parameters) data to simulate different physical processes. The DEM was used to create slope map and discretize networks and sub-watersheds. In addition to DEM, Land use map and Soil map were used to define HRUs. For NRW and SRW, the areas of 0.94 km^2 and 0.54 km^2 have been discretized into 17 sub-watersheds with 350 HRUs, and 10 sub-watersheds with 268 HRUs, respectively.

The DEM data was obtained from Alaska Satellite Facility (ASF, 2019) with a spatial resolution of 12.5 meters. Then, a DEM was generated with a spatial resolution of 5 meters by contouring vectors. Land use maps were created from the interpretation and classification of Landsat satellite images (Ladsat8/OLI images) and confirmed in a field survey. Soil Map was obtained by Tornquist (2007) with a scale of 1:10,000, and the main soil properties (soil granulometry, bulk density, total porosity, available water capacity, and saturated hydraulic conductivity for each soil horizon) were obtained by Ebling (2018) and added to SWAT user soils databases.

The model requires continuous long-term meteorological data, such as precipitation, temperature (maximum and minimum), wind speed, solar radiation, and relative humidity. Daily records from 2014 to 2019 of these climate data were obtained at a station near the watersheds, located in the municipally of Ibirubá, collected by the Brazilian National Institute of Meteorology (Inmet). Surface runoff was simulated using the Soil Conservation Service (SCS) curve number (CN) method (Soil Conservation Service, USDA 1972). Potential evapotranspiration (PET) was calculated using the Priestley-Taylor method (Priestley and Taylor, 1972). Sediment yield was predicted for each sub-watershed based on Modified Universal Soil Loss Equation (MUSLE) (Williams, 1995).

4.2.3.2 Sensitivity analysis, calibration and validation

Daily measured water and sediment yield data were simulated to use in sensitivity analysis, calibration, and validation. These data were measured for the period from 2016 to 2019. 2016, 2018, and 2019 were used for calibration, and 2017 for validation. The meteorological data of 2014 and 2015 were used for model warm-up. The SWAT sensitivity analysis, calibration, and validation were performed using the SWAT-CUP program by Sequential Uncertainty Fitting version 2 (SUFI-2) algorithm (Abbaspour, 2007). The SUFI-2 can estimate a large number of parameters and model uncertainties in hydrological models (Abbaspour, 2007). Within SWAT-CUP, sensitivity analysis was made using global sensitivity analysis that allows changing each parameter at a time (Abbaspour, 2008) and can select the most sensitivity parameters that could influence the observed outputs (water and sediment yield). P-value was used to evaluate the significance of relative sensitivity, in which a p-value close to zero represents higher significance (Abbaspour, 2008). Using the sensitive parameters, the calibration and validation processes were initially performed for water yield, and then for sediment yield.

The performance of SWAT model was evaluated based on the statistical indicators and the performance rating according to Moriasi et al. (2007) for simulation of water and sediment yield at daily time step. The statistical indicators were: coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE), and Percent Bias (PBIAS), presented in equations 1 to 3.

$$R^2 = \left[\frac{\sum_{i=1}^{n} (Y_{obs} - \overline{Y_{obs}})(Y_{sim} - \overline{Y_{sim}})}{\sqrt{\sum_{i=1}^{n} (Y_{sim} - \overline{Y_{sim}}) * \sum_{i=1}^{n} (Y_{obs} - \overline{Y_{obs}})}} \right]^2 \quad (1)$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_m^{obs}\right)^2} \right] \quad (2)$$

$$PBIAS = 100 * \frac{\sum_{1}^{n} (Y_{obs} - Y_{sim})^2}{\sum_{1}^{n} (Y_{obs} - \overline{Y_{sim}})^2} \quad (3)$$

where Y_{sim} is the value simulated from the model, $\overline{Y_{sim}}$ is the average value between the simulated values, Y_{obs} is the value observed in field, and $\overline{Y_{obs}}$ is the average value between the measured data. R^2 ranges from 0 to 1 and quantifies the proportion of explained variance in observed data, with higher values indicating less error variance. NS also ranges from 0 to 1 and estimates the relative magnitude of residual variance as compared to observed data (Nash and Sutcliffe, 1970), and P_{bias} measures the average tendency of simulated data to be under (positive values) or overestimation (negative values) than observed data.

4.2.3.3 Individual and combined BMPs simulations

SWAT model has been widely used to evaluate the effectiveness of implementation of soil and water conservation measures about watershed sediment yield in many areas of the world (Strauch et al., 2013; Uniyal et al., 2020; Ricci et al., 2020; Gashaw et al., 2021; Wang et al., 2021). In this study, after calibration and validation of water and sediment yield in daily time step, some Best Management Practices (BMPs) and combined BMPs were modeled to evaluate the effectiveness in decreasing soil erosion. Firstly, critical sub-watersheds that have high average annual water and sediment yield were identified, and then, BMPs were implemented in all sub-watersheds.

The choice of BMPs considered the four principles of soil conservation: covering the soil to protect it from raindrop impact, increasing the infiltration capacity of the soil to reduce runoff, improving soil structure, and increasing surface roughness to reduce the velocity and volume of surface runoff (Bertoni and Lombardi Neto, 2014). According to Bertoni and Lombardi Neto (2014), the various conservation measures can be described under three approaches:

- Soil Management: is concerned with measures of preparing soil to promote better plant growth and improve its structure becoming the soil more resistant to erosion, such as conservation tillage, residue management, and organic fertilizer application;
- Vegetative Measures: utilize the role of vegetation to protect the soil against the raindrop and surface runoff impacts, such as crop rotation, cover crop, and strip cropping;
- Mechanical Methods: often involving engineering structures that improve the surface topography to control the surface runoff, such as contour farming, terracing, and grassed waterways.

In our study, nine individual BMPs were designed and tested based on these approaches: residue management (SOIL_BMP1), manure application (SOIL_BMP2), conservation tillage (SOIL_BMP3), strip cropping (VEG_BMP1), crop rotation and cover crop (VEG_BMP2), grazing management (VEG_BMP3), grassed waterways (MEC_BMP1), contour farming (MEC_BMP2), and terracing (MEC_BMP3). Summary of BMPs considered in this study, SWAT parameters changes, and the adoption criteria are given in Table 1.

Table 1. Potential BMPs, SWAT parameters changes and the adoption criteria for Northern and Southern watersheds.

Type of BMP	BMP's	SWAT parameters (input files)	Value of BMP	References	Adoption Criteria
Soil Management	**Residue Management** (SOIL_BMP1)	CN2(.mgt)	-2	Arabi et al. (2007)	Soybean and Corn /All soils / All slopes
		OV_N(.hru)	0.2 (0.5-1 Mg ha^{-1} of residue)		
	Manure application (SOIL_BMP2)	FRT_KG(.mgt)	300 kg/ha	Tuppad et al. (2010)	
		FRT_SURFACE(.mgt)	0.5		
	Conservation tillage (SOIL_BMP3)	CH_N1 (.sub)	0.08	Tuppad et al. (2010)	
		EFFMIX (.mgt, till.dat)	0.25		
		DEPTIL(.mgt, till.dat)	100 mm		
		CNOP(.mgt)	-2		
Vegetative measures	**Strip Cropping** (VEG_BMP1)	STRIP_N(.ops)	adjusted based on the area weighted average values for the strips in the system	Arabi et al. (2008)	
		STRIP_C(.ops)			
		STRIP_CN(.ops)	-3		
		STRIP_P(.ops)	0.3, for slope 0 to 8%; 0.35, for slope 8 to 15%; 0.45, for slope >15%		
	Crop rotation and cover crop (VEG_BMP2)	Input files (.mgt)	CORN/SOYBEAN/GREEN BEAN – WHEAT –OAT – CORN/SOYBEAN/ GREEN BEAN[a]	-	
	Grazing management (VEG_BMP3)	GRZ_DAYS(.mgt)	two 10-days cycle	Vache et al. (2002)	Grassland / All soils (except in Gleysols) / All slopes

Mechanical methods	**Grassed waterways** (MEC_BMP1)	CH_W2(.rte)	10	Arabi et al. (2008)	Soybean and Corn/ Acrisols / Slope>8%
		CH_D(.rte)	0.6		
		CH_N2(.rte)	0.4		
		CH_COV2(.rte)	0.001		
	Contour Farming (MEC_BMP2)	CONT_CN(.ops)	-3	Arabi et al. (2008)	Soybean and Corn / All soils / All slopes
		CONT_P(.ops)	0.5, for slope 0 to 8%; 0.7, for slope 8 to 15%; 0.9, for slope greater than 16%		
	Terracing (MEC_BMP3)	TERR_P (.ops)	0.1, for slope 2 to 8%; 0.14, for slope 8 to 15%; 0.18, for slope greater than 15%	Arabi et al. (2008) ASAE (2003)	Soybean and Corn / Ferralsols, Nitisols and Acrisols / Slope>2%
		TERR_CN (.ops)	-6		
		TERR_SL (.ops)	(0.1*SLOPE+0.9)*100/SLOPE		

a- The crop rotation varied in the different years between corn, soybean, and green bean. In each crop were applicated fertilizers and pesticides to improve the plant growing.

Some studies have demonstrated that combined conservation measures are more effective in controlling erosive processes than only one adopted measure (Didoné et al., 2021; Londero et al., 2018). For this reason, four BMPs scenarios were designed based on the three approaches (Soil management, Vegetative measures, and Mechanical methods) to assess the combined effect of BMPs on reduction of sediment yield (Table 2).

Table 2. Selected scenarios with different combinations of BMPs for Northern and Southern watersheds.

Scenarios	BMP type	Combinations of BMP's
Base Scenario	-	Without BMP's
Scenario 1	Soil Management	(SOIL_BMP1)+(SOIL_BMP2)+(SOIL_BMP3)
Scenario 2	Vegetative measures	(VEG_BMP1)+(VEG_BMP2)+(VEG_BMP3)
Scenario 3	Mechanical methods	(MEC_BMP1)+(MEC_BMP2)+(MEC_BMP3)
Scenario 4	Soil Management, Vegetative measures[a] and Mechanical methods	(SOIL_BMP1)+(SOIL_BMP2)+(SOIL_BMP3)+(VEG_BMP2)+ (VEG_BMP3)+(MEC_BMP1)+(MEC_BMP2)+(MEC_BMP3)

a- Strip cropping (VEG_BMP1) did not include in Scenario 4 because the effect of this BMP is similar of terracing (MEC_BMP3).

Individual (9 conservation practices) and combined BMPs (4 scenarios) were only applied to evaluate the sediment yield because there was minimal effect of BMPs on water yield. However, individual BMPs were evaluated at watershed scale for both watersheds, and combined BMPs (four Scenarios) were evaluated at watershed and sub-watershed scale.

Lastly, the impact of water balance components as surface runoff, total aquifer recharge, percolation, evapotranspiration, and baseflow was simulated for each combined BMPs Scenario and compared to base scenario in the SWAT model.

4.3 RESULTS

4.3.1 Sensitivity analysis and model performance

Model sensitivity analysis based on p-value and the fitted value of water and sediment yield parameters are shown in Table 3. We selected fifteen and eight parameters for water and sediment yield calibration, respectively. The most sensitive water yield parameters were ALPHA_BF, CN2, ESCO, GW_DELAY, LAT_TTIME, SOL_AWC, and SOL_BD. The most sensitive sediment yield parameter for both watersheds was RILL_MULT, followed by USLE_K for the Northern watershed, and EROS_EXPO and C_FACTOR for the Southern watershed.

Table 3. P-value and fitted values of the calibrated parameters for water and sediment yield simulations in Northern (NRW) and Southern (SRW) watersheds.

Calibrated variable	Parameters	Name	P-value		Fitted value	
			NRW	SRW	NRW	SRW
Water yield	Baseflow alpha factor (days)	v__ALPHA_BF.gw	0.01	0.00	0.09	0.26
	Effective hydraulic conductivity in main channel alluvium (mm/hr)	r__CH_K2.rte	0.65	-	0.01	-
	Manning's "n" value for the main channel	r__CH_N2.rte	0.65	-	-0.03	-
	SCS runoff curve number	r__CN2.mgt	0.00	0.00	0.01	0.09
	Soil evaporation compensation factor	v__ESCO.hru	0.00	0.00	0.83	0.78
	Groundwater delay time (days)	v__GW_DELAY.gw	0.00	0.00	160.63	16.96
	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H2O)	v__GWQMN.gw	0.00	-	2807.21	-
	Groundwater "revap" coefficient	v__GW_REVAP.gw	-	0.98		0.09
	Average slope steepness (m/m)	r__HRU_SLP.hru	0.67	-	-0.07	-
	Lateral flow travel time (days)	v__LAT_TTIME.hru	0.00	0.00	2.75	1.64
	Manning's "n" value for overland flow	r__OV_N.hru	0.46	-	-0.18	-
	Deep aquifer percolation fraction	v__RCHRG_DP	-	0.14	-	0.06
	Available water capacity of the soil layer (mm H2O/mm soil)	r__SOL_AWC.sol	0.00	0.00	0.09	-0.27
	Moist bulk density (g/cm3)	r__SOL_BD.sol	0.00	0.00	0.13	0.09
	Saturated hydraulic conductivity (mm/hr)	r__SOL_K.sol	0.31	-	0.25	-

Sediment yield	Channel erodibility factor	v__CH_COV1.rte	0.71	0.85	0.25	0.50
	Peak rate adjustment factor for sediment routing in the main channel	v__PRF_BSN.bsn	0.56	-	0.33	-
	Linear parameter for maximum amount of sediment reentrained in channel sediment routing	v__SPCON.bsn	0.41	0.23	0.01	0.01
	Exponential coefficient for overland flow	v__EROS_EXPO.bsn	-	0.00	-	1.58
	Rill erosion coefficient	v__RILL_MULTI.bsn	0.00	0.00	1.02	1.03
	Scaling parameter for cover and management factor for overland flow erosion	v__C_FACTOR.bsn	-	0.00	0.06	0.03
	USLE equation soil erodibility	r__USLE_K.sol	0.00	-	0.18	-
	Peak rate adjustment factor for sediment routing in the subbasin	v__ADJ_PKR.bsn	0.76	-	1.30	-

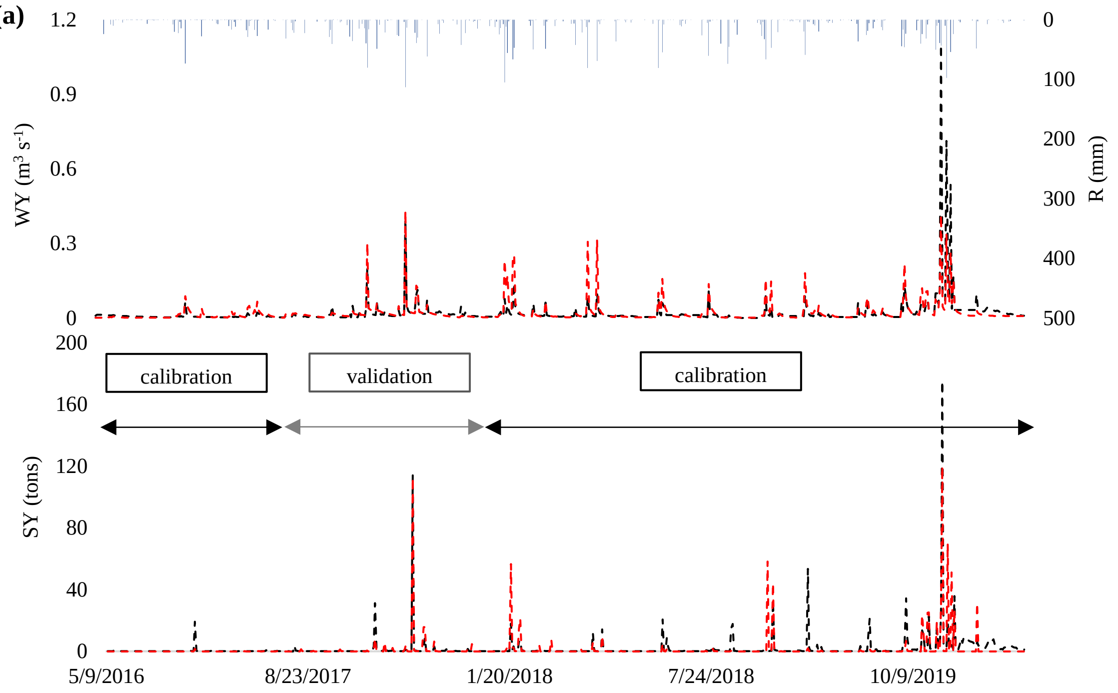
The models showed satisfactory performance in calibration (years of 2016, 2018 and 2019) and validation (2017) of water and sediment yield. The observed and simulated average daily water yield during the calibration and validation were similar, 0.020 m^3 s^{-1} for the Northern watershed and 0.025 m^3 s^{-1} for the Southern watershed. For SY, the simulated data was less than the observed for both watersheds. Observed and simulated average SY of NRW were 1.98 and 1.28 Mg yr^{-1} for calibration, and 1.45 and 1.40 Mg yr^{-1} for validation, respectively. In the SRW, observed and simulated average SY were 0.26 and 0.18 Mg yr^{-1} for the calibration, and 0.49 and 0.24 Mg yr^{-1} for the validation period, respectively. Model performance statistics are summarized in Table 4. NS and R^2 of water yield calibration and validation for watersheds were more than 0.5, and P_{bias} ± 24.4%. For sediment yield simulation, the NS and R^2 were more than 0.4, and P_{bias} ± 35.6%. According to Moriasi et al. (2007), the model can be classified as satisfactory if NS >0.5 and P_{bias} ± 25% for water yield and P_{bias} ± 55% for sediment yield at monthly time scale. However, these criteria for increased temporal resolution (e.g., daily scale) should be relaxed slightly, mainly for sediment yield simulations.

Table 4. Model performance statistics of water yield and sediment yield in the calibration (2016, 2018, and 2019) and validation (2017) period in Northern (NRW) and Southern (SRW) watersheds.

Calibrated variable	Simulation period	NRW			SRW		
		NS	R^2	PBIAS	NS	R^2	PBIAS
Water yield	calibration	0.5	0.5	-9.8	0.5	0.5	5.4
	validation	0.9	1.0	-24.4	0.6	0.7	-23.2
Sediment yield	calibration	0.5	0.5	35.6	0.4	0.4	22.3
	validation	0.9	0.9	3.3	0.4	0.4	30.6

The hydrographs and sedimentographs in Figure 2 demonstrated the performance of the models allowed the reproduction of the daily temporal variability in observed water and sediment yield. While the model performed well to simulate water and sediment yield, several peaks were underestimated during the wet period and overestimated during low flow periods. The year of 2019 was a wet one for both watersheds, in which the simulated WY and SY were underestimated. For example, in the highest recorded event, on October 31, 2019, WY was underestimated almost 61% for the watersheds (observed WY of 1.09 and 0.43 $m^3 s^{-1}$, and simulated of 0.42 and 0.17 $m^3 s^{-1}$ for the NRW and SRW, respectively). SY simulation was 32% and 63% less than the observed SY for the NRW and SRW, respectively. Overall, the SY calibration and validation for both watersheds were underestimated, indicated by the positive values of P_{bias}, and for WY calibration and validation were overestimated (except in SRW validation), indicated by the negative P_{bias}. Furthermore, the baseflow simulation in the SRW was overestimated in most of the observed period (Figure 2b).

(a)



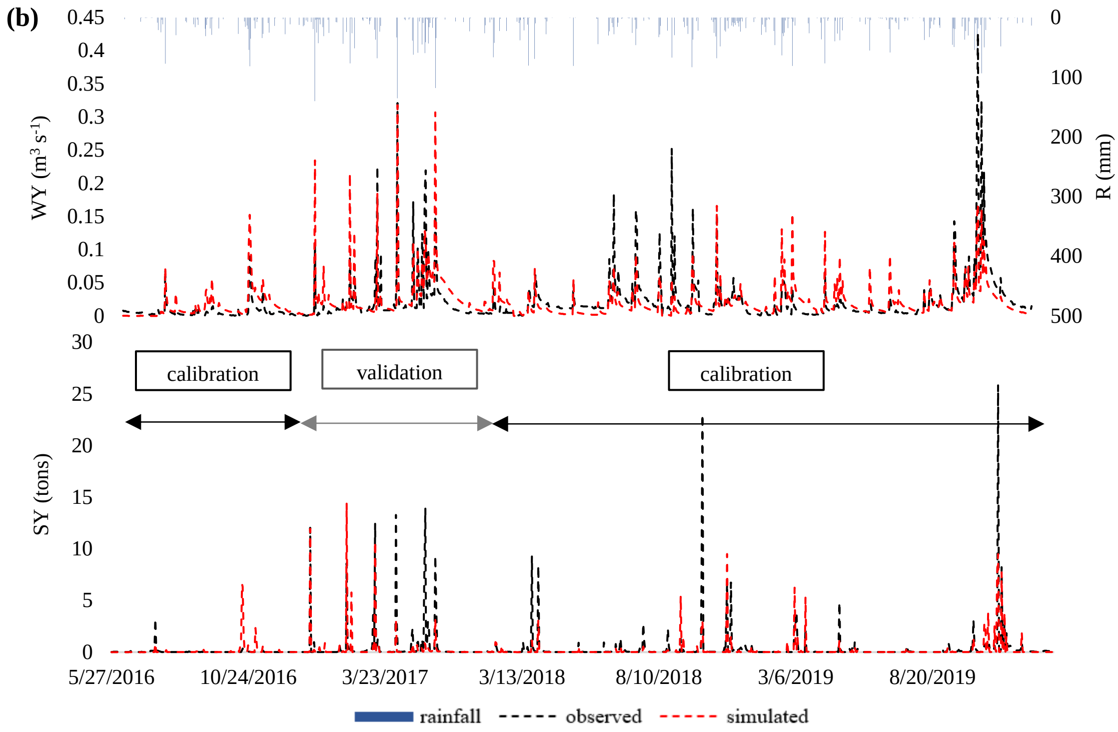


Figure 2. Daily simulated and observed water yield (WY) and sediment yield (SY) calibration and validation in (a) Northern and (b) Southern watersheds.

4.3.2 Water yield and sediment yield responses in paired watersheds

Based on simulated data, the average annual water (WY) and sediment yield (SY) were 0.003 $m^3\ s^{-1}\ yr^{-1}$ and 11.20 Mg $ha^{-1}\ yr^{-1}$ for the Northern watershed, and 0.005 $m^3\ s^{-1}\ yr^{-1}$ and 4.57 Mg $ha^{-1}\ yr^{-1}$ for the Southern watershed. The water and sediment yield varied considerably into sub-watersheds. Figure 3 shows the average annual water and sediment yield at each sub-watershed. Water yield ranged from 0.0003 (SW4) to 0.0131 $m^3\ s^{-1}\ yr^{-1}$ (SW5), and sediment yield was from 0.19 (SW6) to 89.7 Mg $ha^{-1}\ yr^{-1}$ (SW5) for NRW and between 0.0006 (SW7) to 0.016 $m^3\ s^{-1}\ yr^{-1}$ (SW1), and 0.29 (SW9) to 18.09 Mg $ha^{-1}\ yr^{-1}$ (SW5) for SRW, respectively.

The annual average water ($m^3\ s^{-1}\ yr^{-1}$) and sediment yield (Mg $ha^{-1}\ yr^{-1}$) from each sub-watershed were regrouped into different scales according to the behavior of both watersheds and to identify the critical sub-watersheds (Figure 3). The obtained water yield was categorized into four classes: 0-0.001 $m^3\ s^{-1}\ yr^{-1}$, 0.001-0.005 $m^3\ s^{-1}\ yr^{-1}$, 0.005-0.01 $m^3\ s^{-1}\ yr^{-1}$, and >0.01 $m^3\ s^{-1}\ yr^{-1}$. The sediment yield was categorized into five classes: 0-5 Mg $ha^{-1}\ yr^{-1}$, 5-15 Mg $ha^{-1}\ yr^{-1}$, 15-50 Mg $ha^{-1}\ yr^{-1}$, 50-80 Mg $ha^{-1}\ yr^{-1}$, and >80 Mg $ha^{-1}\ yr^{-1}$. Most of sub-watersheds from NRW (85%) are under WY less than 0.005 $m^3\ s^{-1}\ yr^{-1}$, followed by 13.7% between 0.005 to 0.01 $m^3\ s^{-1}\ yr^{-1}$, and only 1.3% of total area with WY more than 0.01 $m^3\ s^{-1}\ yr^{-1}$. The SRW showed more water yield compared to NRW, in which the average WY of SRW was 40%

higher than the NRW and larger area with WY more than 0.01 m^3 s^{-1} yr^{-1}. Therefore, 35.7% of total SRW showed WY less than 0.005 m^3 s^{-1} yr^{-1}, 42.3% between 0.005 to 0.01 m^3 s^{-1} yr^{-1}, and 22% more than 0.01 m^3 s^{-1} yr^{-1}. The annual average sediment yield for NRW and SRW was 57.3 and 67.4% less than 5 Mg ha^{-1} yr^{-1}, 36.3 and 27% between 5 to 15 Mg ha^{-1} yr^{-1}, 5.1 and 5.6% from 15 to 50 Mg ha^{-1} yr^{-1}, respectively. Only NRW showed SY more than 80 Mg ha^{-1} yr^{-1}, representing 1.3% of the total area.

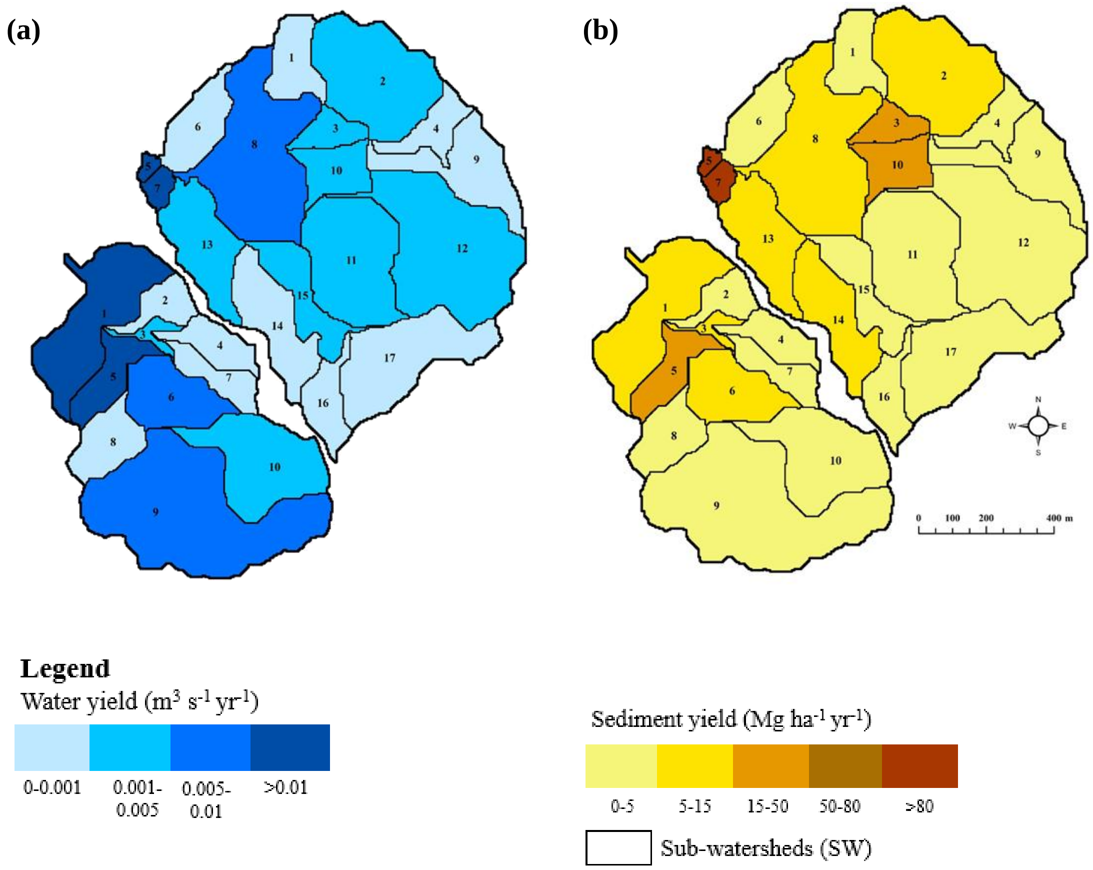


Figure 3. Average annual (a) water and (b) sediment yield at each sub-watershed under base scenario in Northern (NRW) and Southern (SRW) watersheds.

The most critical sub-watersheds for water and sediment yield were SW5 and SW7 for NRW and SW1 and SW5 for SRW, located near the outlet of each watershed (Figure 3a and 3b). Most of HRUs from the NRW and SRW's critical sub-watersheds belong to land cover type of cropland (corn) and grassland (SRW) associated with the higher slope (>8%) and unpaved road (NRW). Among sub-watersheds with a lower sediment yield rate (less than 5 Mg ha^{-1} yr^{-1}) are located southeast of both watersheds. The majority of these HRUs corresponds to a high percentage of native forest for NRW and less slope for SRW.

Into the different land uses, we could observe that 80% of SY are from unpaved road, 10% from soybean, 8% from corn, 1.5% from grassland, and 0.5% from native forest for both watersheds.

4.3.3 Impact of BMPs at watershed scale

Simulations of the nine BMPs showed the reduction of average annual sediment yield for Northern and Southern watersheds (Figure 4a). Only BMPs of manure application (SOIL_BMP2) and grazing management (VEG_BMP3) did not affect the reduction of SY at watershed scale for SRW and NRW, respectively. The simulated average annual sediment yield at the base conditions was 11.20 Mg ha^{-1} yr^{-1} and 4.57 Mg ha^{-1} yr^{-1} for NRW and SRW, respectively.

After the implementation of residue management (SOIL_BMP1), manure application (SOIL_BMP2), conservation tillage (SOIL_BMP3), strip cropping (VEG_BMP1), crop rotation and cover crop (VEG_BMP2), grazing management (VEG_BMP3), grassed waterways (MEC_BMP1), contour farming (MEC_BMP2), and terracing (MEC_BMP3) provided the average annual sediment yield of 10.15, 11.15, 10.23, 9.72, 6.90, 11.19, 11.02, 8.11 and 8.92 Mg ha^{-1} yr^{-1} for NRW, and 4.29, 4.57, 4.26, 4.20, 3.25, 4.55, 4.15, 4.20 and 3.93 Mg ha^{-1} yr^{-1} for SRW, respectively.

Thereby, the Northern and Southern sediment yield has reduced by 9.3 and 6.0% for SOIL_BMP1, 0.4 and 0% for SOIL_BMP2, 8.7 and 6.7% for SOIL_BMP3, 13.2 and 8.1% for VEG_BMP1, 38.4 and 28.8% for VEG_BMP2, and 0 and 0.4% for VEG_BMP3, 1.6 and 9.1% for MEC_BMP1, 27.6 and 8.1% for MEC_BMP2, and 20.4 and 13.9% for MEC_BMP3, respectively. The most effective BMPs at each approach were residue management (SOIL_BMP1) and conservation tillage (SOIL_BMP3) for soil management; Crop rotation and cover crop (VEG_BMP2) for vegetative measures; and contour farming (MEC_BMP2) and terraces (MEC_BMP3) for mechanical methods. Hence, the highest reduction efficiency was VEG_BMP2 for both watersheds, followed by MEC_BMP3 for NRW and MEC_BMP4 for SRW. However, blending these BMPs could improve the efficiency of SY reduction.

4.3.4 Impact of combined BMPs at watershed and sub-watershed scale

After evaluating the impact of each BMP to reduce the average annual sediment yield, four scenarios were built with combined of the three approaches of BMPs: Scenario 1 (soil management BMPs: SOIL_BMP1, SOIL_BMP2, and SOIL_BMP3), Scenario 2 (vegetative measures: VEG_BMP1, VEG_BMP2, and VEG_BMP3), Scenario 3 (mechanical methods:

MEC_BMP1, MEC_BMP2, and MEC_BMP3), and Scenario 4 (all BMPs, except VEG_BMP1). The average annual sediment yield and reduction efficiency of the four scenarios were greater than individual BMPs (Figure 4b), except for the combined mechanical methods in the NRW.

The highest sediment reduction efficiency at watershed scale (46% and 41.5% for NRW and SRW, respectively) was achieved by the implementation of combined all BMPs (Scenario 4) that provided the average annual sediment yield of 6.05 and 2.67 Mg ha^{-1} yr^{-1} for NRW and SRW, respectively. Followed by the vegetative (Scenario 2), mechanical (Scenario 3), and soil scenarios (Scenario 1) with a reduction of 43.5 and 34.1%, 14.6 and 16%, and 9.9 and 6.8% for NRW and SRW compared to base scenario, respectively.

(a)

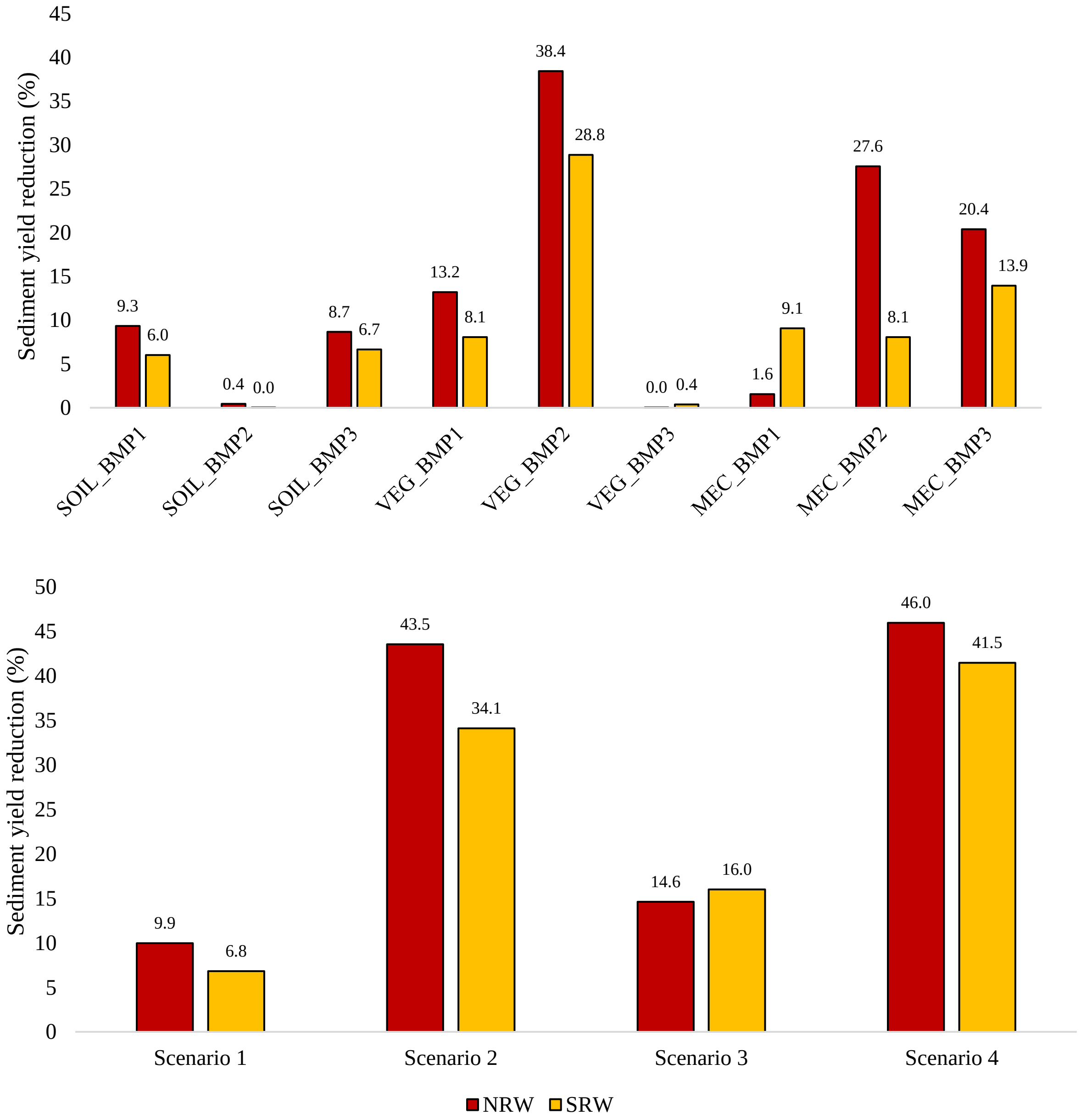
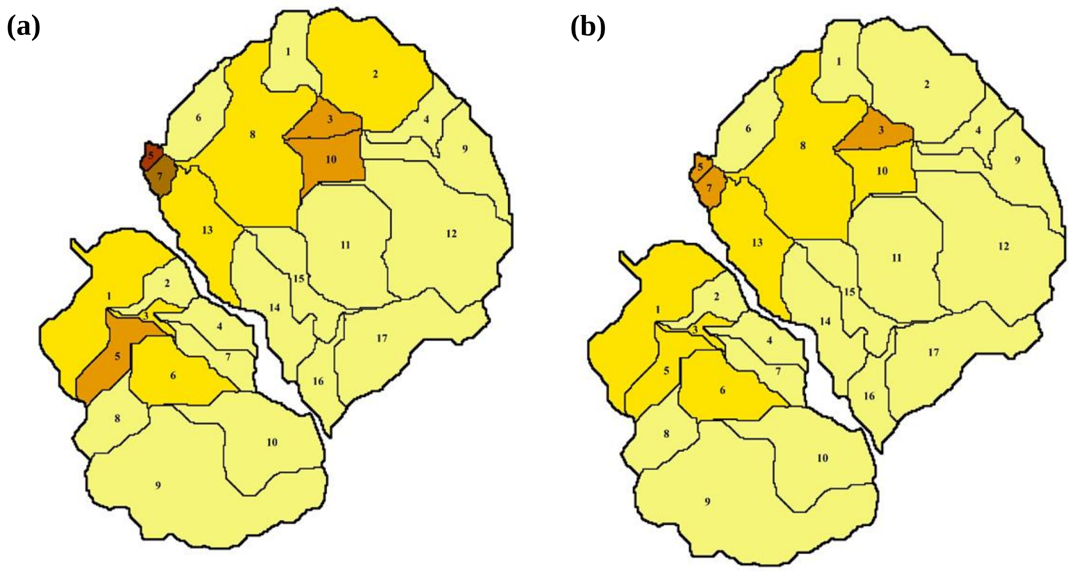


Figure 4. Sediment yield reductions (%) at (a) individual BMPs and (b) combined BMPs (Scenarios) compared to the Base scenario in Northern (NRW) and Southern (SRW) watersheds.

The simulated annual average sediment yield from sub-watersheds under the four scenarios is shown in Figure 5. Average annual of SY from Base Scenario of NRW and SRW sub-watersheds ranged from 0.19 (SW6) to 89.73(SW5) Mg ha^{-1} yr^{-1} and 0.29 (SW9) to 18.09 (SW5) Mg ha^{-1} yr^{-1}, respectively (Figure 3b). At the implementation of Scenario 1, the average annual sediment yield ranged from 0.17 (SW6) to 81.11 (SW5) Mg ha^{-1} yr^{-1} for NRW, and from 0.27 (SW9) to 16.97 (SW5) Mg ha^{-1} yr^{-1} for SRW (Figure 5a). This scenario affected more the NRW than SRW, in which the SY class from SRW critical sub-watersheds have not shifted. In the application of Scenario 1 in NRW, only SW7 moved down from class more than 80 Mg ha^{-1} yr^{-1} to class between 50-80 Mg ha^{-1} yr^{-1}. This scenario has also moved down SW14 of NRW to class less than 5 Mg ha^{-1} yr^{-1} (increase 6% of total area in this class). The sediment yield with the implementation of Scenario 1 has reduced from 0 to 10% in critical sub-watersheds, and 10 to 30% in the other sub-watersheds, with the highest SY reduction (20-30%) detected in SW16 from NRW (Figure 6a).



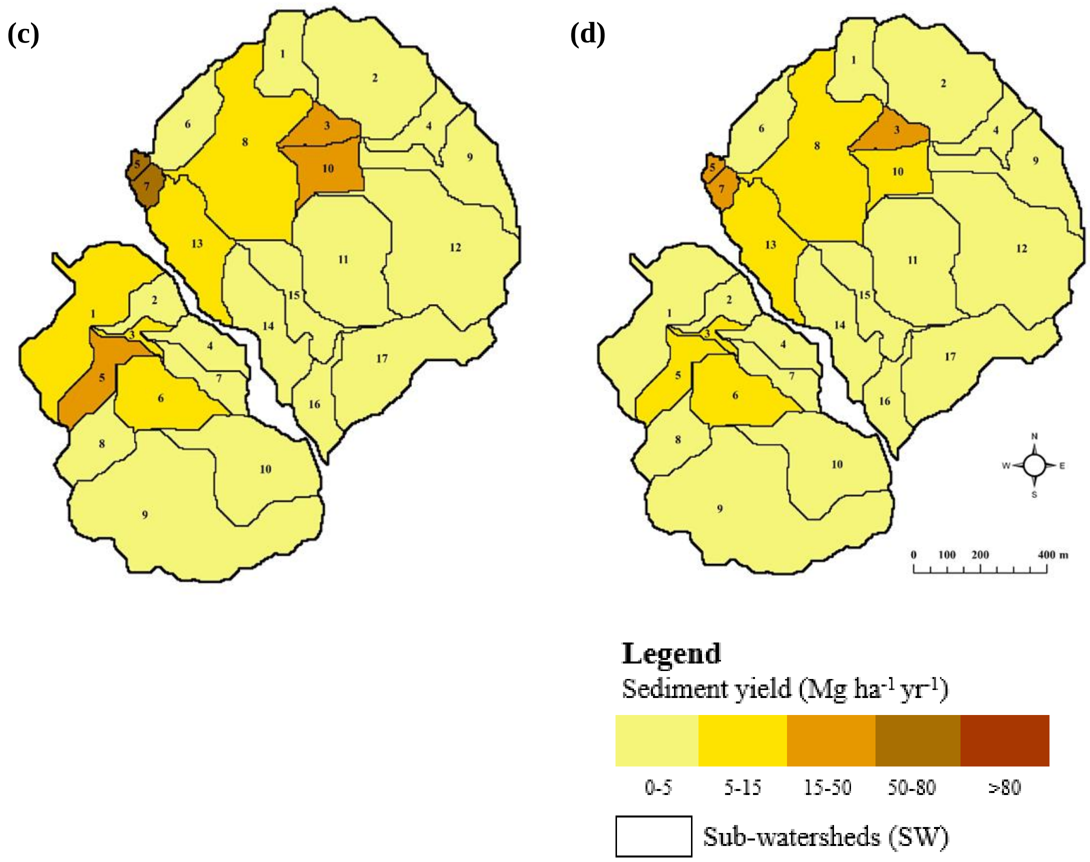
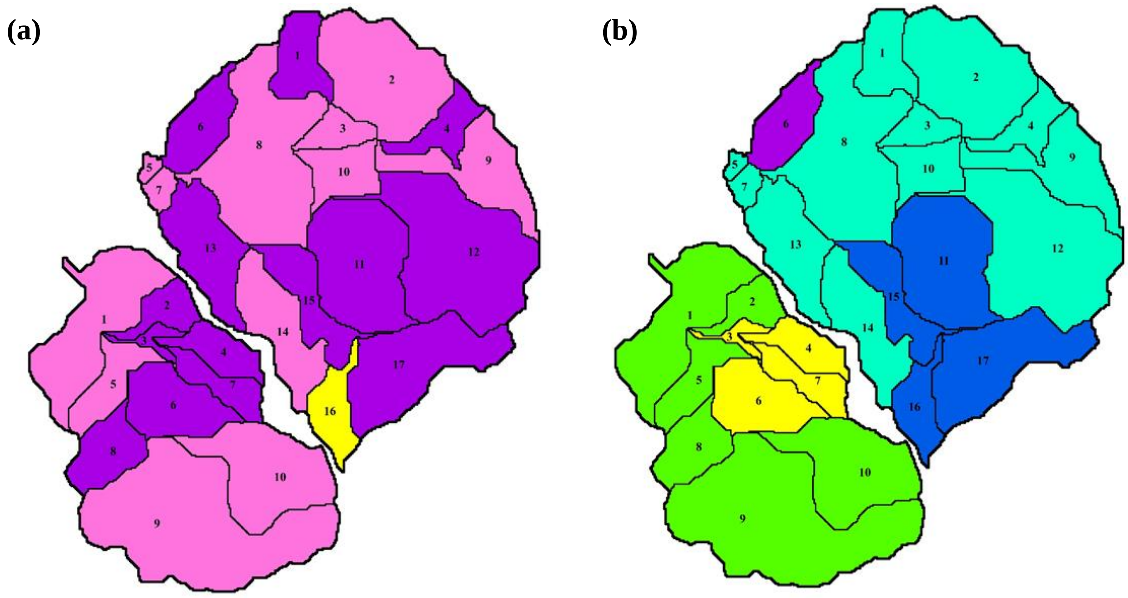


Figure 5. Mean annual sediment yield at each sub-watershed under (a) Scenario 1, (b) Scenario 2, (c) Scenario 3, and (d) Scenario 4 in Northern and Southern watersheds.

The average annual sediment yield of NRW and SRW under Scenario 2 ranged from 0.15 (SW6) to 48.88 (SW5) Mg ha^{-1} yr^{-1} and 0.19 (SW9) to 11.87 (SW5) Mg ha^{-1} yr^{-1}, respectively (Figure 5b). The application of this scenario affected the critical sub-watersheds for both watersheds. NRW's critical sub-watersheds (SW5 and SW7) moved down from SY class more than 80 Mg ha^{-1} yr^{-1} to class between 15 to 50 Mg ha^{-1} yr^{-1}, and the SW5 from SRW shifted from SY class between 15 to 50 Mg ha^{-1} yr^{-1} to class 5 to 15 Mg ha^{-1} yr^{-1} (an increase of 6% of total area in this class). This scenario has also shifted SW14 from NRW to class less than 5 Mg ha^{-1} yr^{-1} (increase 16.4% of total area in this class), and the SW10 to class between 5 to 15 Mg ha^{-1} yr^{-1}. The implementation of the Vegetative scenario reduced SY between 10 to 60%, with a reduction of 40 to 50%, representing 70% of total NRW (including the critical sub-watersheds), and a reduction from 30 to 40%, representing 80% of total SRW (Figure 6b).

The mechanical scenario (Scenario 3) decreased the average annual SY in both watersheds that varied from 0.19 (SW6) to 76.46 (SW5) Mg ha^{-1} yr^{-1} for NRW, and 0.27 (SW9) to 15.11 (SW5) Mg ha^{-1} yr^{-1} for SRW (Figure 5c). The critical sub-watersheds for NRW (SW5 and SW7) shifted from the highest SY class (>80 Mg ha^{-1} yr^{-1}) to class between 50 to 80 Mg ha^{-1} yr^{-1}. SW2 and SW4 from NRW have also shifted to the soil loss class less than 5 Mg ha^{-1} yr^{-1}. The implementation of Scenario 3 did not modify SY classes of SRW sub-watersheds. However, the reduction of sediment yield ranged from 0 to 30% for both watersheds, in which 65% of total area from NRW reduced between 10 to 20%, and 60% of SRW area reduced from 0 to 10% (Figure 6c).

Scenario 4 was the association of all BMPs types (soil, vegetative and mechanical measures), and this showed the most effective to decrease sediment yield in both watersheds (Figure 5d and 6d). The average annual SY ranged from 0.14 (SW6) to 48.38 (SW5) Mg ha^{-1} yr^{-1} for NRW and 0.19 (SW6) to 10.26 (SW5) Mg ha^{-1} yr^{-1} for SRW (Figure 5d). Compared to base scenario, the sub-watersheds from NRW shifted as the vegetative scenario (Scenario 2). However, SW1 and SW5 from SRW moved down to SY class less than 5 (increased 16% of total SRW) and between 5 to 15 Mg ha^{-1} yr^{-1}, respectively. Reduction of SY varied from 20 to 60% in this scenario, in which 96% of total area from NRW reduced between 40 to 60%, and 90% of SRW total area from 30 to 50% (Figure 6d).



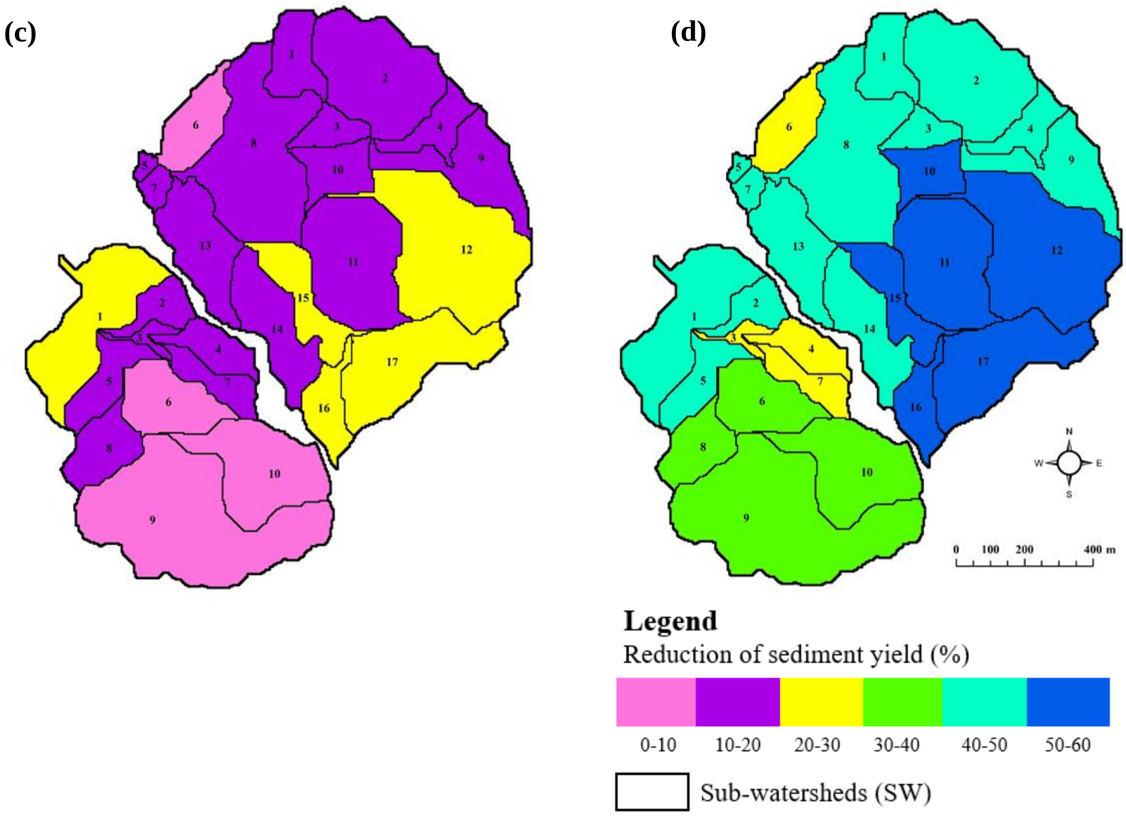


Figure 6. Reduction of sediment yield (%) at each sub-watershed after implementation of (a) Scenario 1, (b) Scenario 2, (c) Scenario 3, and (d) Scenario 4 in Northern and Southern watershed.

4.3.5 Impact of combined BMPs on water balance components

Average annual water balance components have been estimated (2016-2019) for the base scenario and the four combined BMPs scenarios at each watershed (Figure 7). In the base scenario, evapotranspiration was more predominant in the NRW and SRW which accounted for 64.5 and 49.5% of the average annual rainfall (1122.3 and 1512.9 mm), respectively. From the rainfall generated flow, 12.4 and 19.6% were as surface runoff, and 7.1 and 28.5% were as baseflow for NRW and SWR, respectively. Results of the implementation of four scenarios indicated a marginal change in the annual average surface runoff, total aquifer recharge, percolation, evapotranspiration, and baseflow for both watersheds (Figure 7). There was a reduction in the surface runoff in all scenarios for SRW and NRW compared to Base scenario, ranging from -14.8 to -6.4%.

The reduction in the surface runoff could be supported by an increase in total aquifer recharge (3.1 to 14.8% for NRW, 2.7 to 5.8% for SRW), an increase of percolation (3.8 to 17.3% for NRW, 2.6 to 5.5% for SRW) and an increase of baseflow (2.9 to 13.86% for NRW, 2.7 to 5.9% for SRW), and a decrease and increase in evapotranspiration (-5.2 to 0.2% NRW, 0.1 to 2.1% for SRW). The impact in water balance components by Scenario 4 was higher than the other three scenarios in both watersheds, followed by Scenario 2.

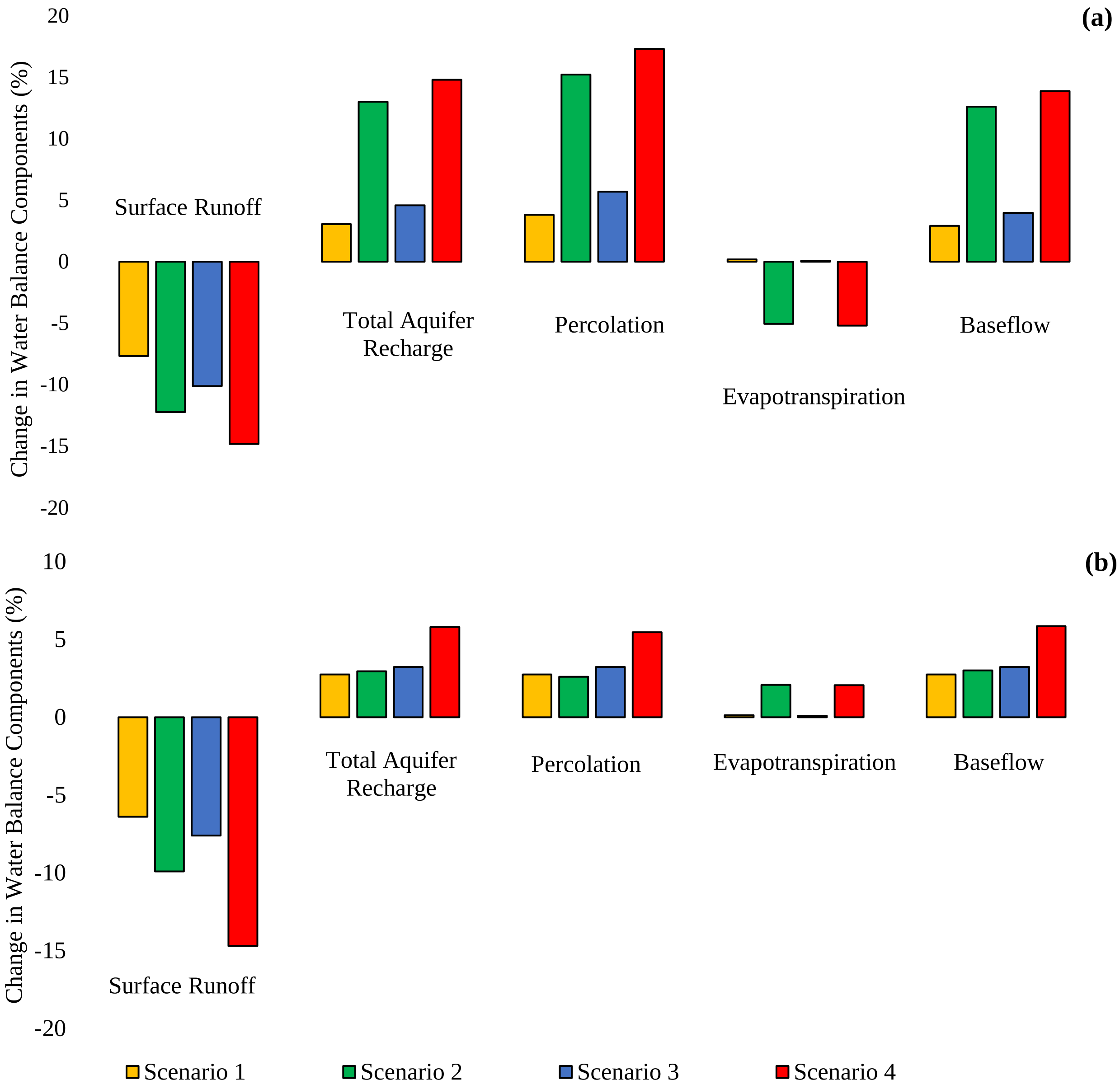


Figure 7. Change in water balance components after implementation the BMPs scenarios in (a) Northern and (b) Southern watersheds.

4.4 DISCUSSION

4.4.1 Soil erosion responses on paired watersheds

Studied paired watersheds consist predominantly of soil classes that are less susceptible to soil erosion, but are associated with high rainfall, steep slope, and cultivated land, which enable soil erosion processes. SWAT model was used after daily water and sediment yield calibration and validation to evaluate the effectiveness of individual and combined BMPs on sediment yield in two agricultural paired watersheds. Firstly, based on simulated and observed data in four years (2016-2019), NRW showed more susceptibility to soil erosion than SRW.

The average annual sediment yield in NRW (11.20 Mg ha^{-1} yr^{-1}) was almost 60% greater than in SRW (4.57 Mg ha^{-1} yr^{-1}). These watersheds are different mainly in size of drainage area and the presence of riparian vegetation (Ebling, 2018). Some studies have reported the presence of riparian vegetation along the drainage network decreases the amount of sediment transported and mobilized to the water bodies (Sirabahenda et al., 2020; Tiecher et al., 2017; Waidler et al., 2011). Riparian vegetation could work as a physical filter that reduces excessive amounts of sediment, nutrients, and pesticides in surface runoff (Broetto et al., 2017; Waidler et al., 2011). Besides, riparian vegetation decreases connectivity between cropland and streams (Tiecher et al., 2017).

Critical sub-watersheds from NRW and SRW showed sediment yields of more than 80 Mg ha^{-1} yr^{-1} and more than 15 Mg ha^{-1} yr^{-1}, respectively. According to the soil erosion class developed for Brazilian conditions by Carvalho (2008), these sub-watersheds can be classified by severe and moderate soil loss. These sub-watersheds were attributed mainly to steep slopes, higher percent of cropland, and grassland associated with the presence of unpaved roads in NRW.

There is a significant association between slope gradient and land use with soil loss. Some studies argued there is a linear effect of slope gradient with soil loss increase (Rieke-Zapp and Nearing, 2005; Zhang et al., 2021), in which steeper slope gradients tend to decrease soil infiltration and increase the velocity of surface runoff, promoting greater erosion and sediment transport (Deng et al., 2020). Although unpaved road covers a small portion of the NRW area, these have shown a significant source of runoff and sediment (~80%). The same was observed by Minella et al. (2007, 2009), the unpaved roads occupied a small portion of the watershed but resulted in a large contribution to soil erosion. Thomaz et al. (2014) showed that drainage areas less than 3 km^2 had more contribution to sediment yield than large areas. Unpaved roads systems may change the hydrologic surface by increasing the concentrated runoff (Wang et al., 2021) and consequently contributing to more sediment yield in these areas. However, the introduction of improved management practices in the fields can reduce sediment yield from unpaved roads. As noted by Minella et al. (2009), the implementation of minimum tillage reduced runoff on fields, and consequently, reduced runoff and soil erosion onto roads.

Previous researches have shown that land use is the key factor that affects soil erosion (Anache et al., 2017) due to minimize the effect of rainfall splashes and surface runoff. For example, under the same rainfall amount, the sediment yield in bare soil and cropland was significantly higher than in natural vegetation (Zhang et al., 2021). Cropland areas are the main sediment source in most watershed studies (Risal et al., 2020; Tiecher et al., 2015, 2018).

Tillage and management in these areas induce soil erosion (Zhao et al., 2018), while adoption of conservation tillage is effective to reduce soil erosion (Blanco-Sepúlveda et al., 2021). Currently, the no-till in both watersheds has been implemented but without the premises of the no-till system, only keep the ground cover from previous crops, resulting in a high water and sediment yield. Thus, it is essential to implement conservation practices in these areas.

4.4.2 Impact of individual and combined BMPs on paired watersheds

The effectiveness of sediment yield reduction of individual BMPs varied from 0 to 38.4% for NRW and 0 to 28.8% for SRW. The most effective conservation practice in both watersheds was crop rotation and cover crop (VEG_BMP2). The VEG_BMP2 is an effective conservation practice to mitigate soil erosion due to higher soil cover and roughness resulting from different vegetations (Didoné et al., 2017). The NRW and SRW are characterized by intensive soybean/corn monoculture which limits the effects of crops diversity. For example, da Silva et al. (2021) showed that soybean monoculture had similar soil, water, and nutrient losses as bare soil. Therefore, the implementation of crop rotation and cover crop enhances soil environmental and agronomic functions by increasing rainfall intercept, which minimizes the direct impact of raindrops on the soil surface, and decreases surface sealing (Blanco-Canqui & Ruis, 2018).

The second most effective individual BMPs were contour farming for NRW and terraces for SRW that SY reduced 27.6 and 13.9%, respectively. Both BMPs were considered mechanical methods in this study, in which the purpose is to reduce the velocity and volume of surface runoff. Terraces can substantially reduce runoff, especially during heavy rainfall events. Ran et al. (2020) showed that under a rainfall intensity of 120 mm h^{-1}, a well-maintained terrace could reduce runoff by 100% compared to a natural hillslope. However, the major limitation of terracing is caused by poor management, which could increase soil loss from 1 to 5 times than well-management terraces (Deng et al., 2021). In contrast, in some studies (Briak et al., 2019; Didoné et al., 2021; Karlen et al., 2009), the implementation of contour farming was highly effective in controlling erosive processes in both watersheds. Dibaba et al. (2021) also had a high reduction of contour farming, but terracing resulted in a higher reduction of soil loss than contour farming.

After testing the implementation of individual BMPs, combined BMPs were tested to evaluate the most efficient approach in both watersheds. Among the three approaches to soil, vegetative and mechanical conservation measures, the combined vegetative measures (Scenario 2) were the most effective to reduce sediment yield at watershed (reduction of 43.5% for NRW and 34.1% for SRW) and sub-watershed (reduction from 10 to 60% for both watersheds) scale. The combination of both conservation practices reduces the effect of raindrop impact by cover crop, besides reducing the velocity of surface runoff from strip cropping and soil-transporting capacity, and, consequently, decreases soil loss (Laufer et al., 2016; Wischmeier and Smith, 1978). Laufer et al. (2016) showed that strip cropping with crop rotation could reduce 92 and 98% of surface runoff and soil loss compared to intensive tillage, respectively.

Mechanical methods (Scenario 3) were the second combined BMP to sediment yield reduction. Scenario 3 could reduce from 0 to 30% of sediment yield in sub-watersheds for both watersheds. In the combined mechanical BMPs, the reduction of sediment yield is caused by the reduced velocity, volume, peak, and erosive power of surface runoff through impounding water in small depressions and reduced length of hillslope (Arabi et al., 2008; Chen et al., 2012; Huihui et al., 2016). Combined mechanical BMPs decreased the average annual sediment yield at watershed scale and in the critical sub-watersheds from NRW. Contour farming is most effective on gentle and shorter slopes (Jia et al., 2020; USDA, 2017) that longer and steeper slopes, overland flow volume and velocity exceed the capacity of the contour ridges. Therefore, increasing roughness by implementing terraces decrease surface runoff and sediment yield (Fang, 2021; USDA, 2017).

The least efficient scenario between the three approaches was soil management. The benefits of the soil management scenario are to reduce surface runoff by increasing land cover and roughness, improve soil aggregate stability, increase infiltration, and then, decrease soil loss (Arabi et al., 2008). Some studies observed that the positive effects on physical properties and on soil erosion have shown to a long term in implementing these measures (Klik and Rosner, 2020; Nunes et al., 2018; Sithole et al., 2019; Wolschick et al., 2021; Zanon et al., 2020; Zhang et al., 2007).

The implementation of no-till in Brazil has been increasing in the last decade, Fuentes-Llanillo et al. (2021) observed an increase of 84.9% of no-till areas between 2006 and 2017. However, the application of only no-till is not guaranteed for production sustainability and optimization. Zanon et al. (2020) studied the long-term (twenty years) effect on manure application in no-till areas, and observed the improvement in physical, chemical, and biological properties. However, it was not enough to reduce runoff under high-intensity rainfall, even with the presence of straw and absence of surface sealing. Because of this, the association of different types of conservation practices is necessary to minimize the effects of soil erosion.

The most efficient scenario included all types of BMPs (Scenario 4). Scenario 4 reduced sediment yield of 46 and 41.5% for NRW and SRW at watershed scales from base scenario, respectively. From 20 to 60% at sub-watershed scales, which reduced from 40 to 50% in the critical sub-watersheds. Previous studies have reported that the association of vegetative and structural conservation measures is the best way to control soil erosion (Ebabu et al., 2019; Gashaw et al., 2021; López-Ballesteros et al., 2019). For example, Uniyal et al. (2020) indicated the good performance of the combined agronomic and structural BMPs in controlling sediment yield than individual BMPs in the Baitarani watershed (India). Lópes-Ballesteros et al. (2019) associated five structural and agricultural BMPs (reforestation, check dam restoration, contouring, filter strip, and fertilizer application), and found reduced values of sediment yield until 93%, compared to scenario without BMP. In general, mechanical methods are designed to control soil erosion and surface runoff where soil management and vegetative practices are projected to improve soil quality and decrease the impact of raindrops (Morgan, 2005), but these practices alone are insufficient to reduce soil erosion to permissible levels (Blanco and Lal, 2010).

4.4.3 Impact of combined BMPs on water balance components

There was a great impact of combined BMPs on water balance components (surface runoff, total aquifer recharge, percolation, evapotranspiration, and baseflow). Scenario 4 had more impact on water balance components, followed by Scenario 2. In both watersheds, there was a reduction of surface runoff, an increase in total aquifer recharge, percolation, evapotranspiration, and baseflow. This result was similar to Uniyal et al. (2020) that the implementation of three scenarios resulted in a reduction of surface runoff, and then an increase of lateral flow, aquifer recharge, baseflow, and percolation. Base scenario indicated that 12.4 and 19.6% of total rainfall was generated in the surface runoff for NRW and SRW, respectively.

The implementation of all scenarios decreased the surface runoff volume and velocity by increasing and improving in-watershed utilization of water, such as increasing infiltration rate, and in turn minimizing soil erosion (Himanshu et al., 2019). Both watersheds are characterized by predominantly clay soils (Ferralsols and Nitisols) with a moderate soil permeability (Mentges et al., 2016; Holthusen et al., 2018a, 2018b) but high-water retention capacity (Vaz et al., 2005; Reichert et al., 2009, 2020). Improving water infiltration is a key to keeping water available, especially in dry periods. In dry periods, the surface water in watercourses is recharged by groundwater (Fan et al., 2013). However, human activities, including agricultural activities are the main factors reducing baseflow in mainstreams. Li et al. (2021) reported that human activities contributed to a decrease of more than 63% of baseflow in a basin of Northwest China. Thereby, the increase of baseflow and total aquifer recharge and the contribution of groundwater to surface water by conservation practices could be an interesting option for farmers. The evapotranspiration estimated by the SWAT model represented 64.5 and 49.5% for NRW and SRW base scenarios, respectively.

With the implementation of Scenario 2 and 4, we could observe a small decrease and an increase in evapotranspiration for NRW and SRW, respectively. The change in the diversity of vegetations and increase the soil cover by crop cover could provide lower evapotranspiration in NRW. Yang et al. (2018) observed that maize-wheat-soybean rotation under no-till provided higher soil water storage and lower evapotranspiration compared to conventional tillage. But in only maize land, transpiration and evaporation were not significantly changed by the different treatments. The same was found by Boufala et al. (2021), no effect on evapotranspiration was observed in the three BMPs scenarios. In general, Scenario 2 and 4 (Figure 6 and 7) were the most appropriate for the integrated management for both watersheds, which provide a better result to minimize the erosion processes and optimize the water balance in watersheds.

4.4.4 Strengths and Limitations of this study

The findings of this study will contribute to helping decision-makers, farmers, and water resources planners, as it provides information about the most susceptible areas for soil erosion and the implementation of the best management practices to minimize the effects of soil erosion and hydrological processes. One of the lessons learned from this research is that the implementation of only "no-till" is not enough to contain soil erosion, resulting in a high sediment yield rate in both watersheds. However, the adoption of BMPs resulted in soil erosion control for most of the tested BMPs. The most effective individual BMP for both watersheds was VEG_BMP2 (crop rotation and cover crop), indicating that the good management with diverse vegetive crops and to keep surface soil protected could decrease the effects of soil erosion and improve the soil conditions. Besides being a conservation practice of easy implementation for farmers, it has high economic benefits.

Another lesson learned was about the different types of BMPs, in which the association of soil, vegetative and mechanical conservation measures resulted in the best management to decrease soil erosion. For example, Scenario 4 was an effective scenario to reduce soil erosion and optimize water balance components.

Understanding the impact of conservation practices beyond soil erosion, including the water balance, is fundamental to the proper management of soil and water resources at a watershed scale. Lastly, choosing the right control practices is really important due to adequate management give a positive impact on terms of economy.

Based on the outcomes of this study, there are some limitations. First of all, there was an uncertainty associated with modeling due to several factors including lack of hydrossedimentological variables observations and measurements, and limitations to represent the soil erosion and hydrological processes in the SWAT model. Secondly, the water and sediment yield modeling period were small for calibration and validation. Therefore, increasing this period with the monitored data could better represent the soil erosion and hydrological processes. Thirdly, SWAT model does not allow growing two crops in a single HRU simultaneously (Neitsch et al., 2011), which sometimes could underestimation the capacity to reduce soil erosion in some conservation practices such as strip cropping and mixed cultivation.

Lastly, this study showed the efficiency of BMPs implementation in reducing sediment yield and optimizing water balance, but the economic feasibility of these implementations was not evaluated. Economic feasibility by BMPs is an important subject to inform and convince farmers to adopt BMPs in croplands. In general, several barriers limit the adoption of BMPs in many countries.

The beliefs and socio-economic characteristics of farmers, and the lack of knowledge about the causes and effects of soil erosion and the long-term return on economic investments for BMP implementations favor the non-adoption of conservation measures (Ricci et al., 2020; Uphadhaya et al., 2021). Therefore, programs for soil and water conservation must be implemented by the public and private sectors to provide subsidies for farmers (Brazilian programs: “Conservador das águas”, “Programa Bolsa Floresta”, “Conserv”, “Programa Reflorestar”, “Produtor de água”).

4.5 CONCLUSIONS

In this study, the monitoring and modeling of two paired agricultural watersheds were carried out using SWAT model to evaluate the effectiveness of nine potential soil, vegetative and mechanical best management practices (BMPs) to reduce sediment yield.

Very high sediment yields were measured in both watersheds, in which Northern watershed (NRW) showed more susceptibility to soil erosion than Southern watershed (SRW). These results illustrate that the presence of riparian vegetation in SRW helps to reduce sediment yield, and the no-till alone cannot hold soil erosion. About the BMPs simulations, VEG_BMP2 (crop rotation and cover crop) was the most effective individual BMP for both watersheds. The combination of all BMPs approaches (Scenario 4) showed the most effective to reduce sediment yield (46 and 41.5% for NRW and SRW, respectively). Followed by the vegetative combination (Scenario 2) that reduced SY by 43.5 and 34.1% for NRW and SRW, respectively. Scenarios 2 and 4 could reduce from 40 to 50% of sediment yield in the critical sub-watersheds. In cases where applying all measures is not possible, Scenario 2 is a potential scenario that can be used to minimize soil erosion. The implementation of combined scenarios supported improving water balance components, which decreased surface runoff from 6.4 to 14.8%, and increased groundwater components from 2.7 to 18.9% in both watersheds.

In general, the results provide some evidences that the implementation of only one type of conservation measures approach is not enough to reduce soil loss, and the association of the three different BMPs approaches minimizes soil erosion processes and optimizes water balance. However, more studies are needed to assess the impacts of BMP implementation on crop productivity, cost benefits, and in high erosivity and water stress conditions.

The findings of this study could help farmers and decision-makers to choose feasible and appropriate conservation measures to reduce the impact of erosive processes.

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5 DISCUSSÃO INTEGRADA

O uso e manejo do solo são potenciais fatores que afetam os processos hidrológicos e de erosão do solo. Entre os três usos do solo investigados nas quatro pequenas bacias hidrográficas, a maior perda de solo e água foi encontrada nas bacias sob agricultura. A maior perda de solo e água nessas bacias ocorre devido ao intenso manejo associado à menor cobertura do solo. Entre as bacias hidrográficas pareadas agrícolas, a bacia com maior percentagem de vegetação ripária (Bacia Sul) apresentou menor perda de sedimentos. A presença de vegetação ripária diminui a taxa de sedimentos transportado e mobilizado para os cursos d’água (SIRABAHENDA et al., 2020; TIECHER et al., 2017; WAIDLER et al., 2011), além de diminuir a conectividade entre as áreas de maior erosão e os cursos d'água (TIECHER et al., 2017). Por outro lado, a bacia hidrográfica sob *Eucalyptus* apresentou menor perda de solo e água comparada com as demais. Áreas sob floresta plantada tende a apresentar menor perda de água devido à maior interceptação de chuva, maior evapotranspiração, e maior taxa de infiltração proporcionada pelo grande dossel e pela proteção da superfície do solo por serrapilheira, resultando em menor produção de sedimentos (EBLING et al., 2021; FERRETO et al., 2021a; FERRETO et al., 2021b; HU et al., 2021; REICHERT et al., 2017; REICHERT et al., 2021; VALENTE et al., 2021).

A aplicação do modelo SWAT no estudo foi essencial para entender como os processos hidrológicos e de erosão do solo ocorrem em cada bacia hidrográfica. Os processos que controlam as respostas hidrológicas e erosivas variaram nos diferentes intervalos de tempo e nas diferentes bacias hidrográficas (BAFFAUT et al., 2015; GUSE et al., 2019). Por exemplo, na escala de tempo horária, a vazão é controlada pelas características da chuva e pelos fatores que afetam diretamente a formação do escoamento superficial, como características do solo. Por outro lado, em menores resoluções temporais, como mensal e diário, a vazão é controlada por características geomorfológicas e subsuperficiais (BLÖSCHL e SIVAPLAN, 1995). Tais resultados foram enfatizados pela sensibilidade dos parâmetros do modelo nos distintos intervalos de tempo estudados. Conforme Jeong et al. (2010), os parâmetros do modelo correspondentes ao fluxo do canal são mais influentes em resoluções temporais maiores, e os parâmetros correspondentes aos fluxos de água subterrâneas têm mais influência em resoluções temporais menores. Esses resultados enfatizam a necessidade de calibrar os modelos hidrológicos conforme os objetivos dos processos específicos e a escala temporal e espacial que se deseja estudar (BAFFAUT et al., 2015), a fim de obter resultados mais consistentes.

A melhor representação dos hidrogramas e sedimentogramas das bacias agrícolas pareadas foi na escala de tempo diária, a qual foi escolhida para a simulação de cenários de conservação do solo e da água. Alta produção de sedimentos foi observada nessas bacias, sendo possível concluir que apenas a implementação do plantio direto não é o suficiente para conter a erosão do solo (DIDONÉ et al., 2014; LONDERO et al., 2018; LONDERO et al., 2021). Porém, com a associação de outras práticas conservacionistas, o efeito na redução da produção de sedimentos foi significativo. Em contrapartida, embora alguns estudos indiquem maior eficiência com a implementação de práticas mecânicas (LONDERO et al., 2018; DIDONÉ et al, 2021), nossos resultados mostraram uma maior redução da produção de sedimentos ao implementar apenas a rotação de culturas e plantas de cobertura. Portanto, a associação das três abordagens conservacionistas (manejo do solo, práticas agronômicas e métodos mecânicos) resultou em maior eficiência na redução de sedimentos e melhoria dos componentes do balanço hídrico, como também observado para sedimentos (EBABU et al., 2019; GASHAW et al., 2021; LÓPEZ-BALLESTEROS et al., 2019) e hidrologia (HIMANSHU et al., 2019). Novas estratégias integradas de conservação do solo também devem ser testadas, como a alocação de bacias de captação de água em estradas não pavimentadas (STRAUCH et al., 2013), aumento da vegetação ripária em ambas as bacias e testar novos cenários com diferentes combinações de BMPs.

Apesar da modelagem hidrológica apresentar algumas limitações, a representação do comportamento hidrológico e erosivo das bacias hidrográficas está consistente com os resultados observados. Ambos os artigos enfatizam a importância do adequado manejo e uso do solo, sendo fatores determinantes nas respostas hidrológicas e de erosão do solo. Portanto, novas estratégias integradas de conservação do solo e da água podem ser testadas a fim de promover práticas agrícolas sustentáveis e avaliar o custo-benefício da implementação de melhores práticas de manejo. Pesquisas adicionais também podem ser realizadas com a aplicação de outros modelos para avaliar o efeito das mudanças temporais no manejo do solo e em relação as mudanças dos regimes de precipitação.

6 CONCLUSÃO GERAL

O uso do solo tem impacto significativo nos processos hidrológicos e erosivos, no qual as bacias hidrográficas agrícolas foram as mais suscetíveis a erosão do solo e produção de água. Em contrapartida, a bacia hidrográfica sob floresta plantada apresentou menor produção de sedimentos e vazão. O modelo SWAT foi capaz de detectar o impacto do uso do solo sobre os processos em estudo e em diferentes intervalos de tempo. Portanto, há a necessidade de melhoria do modelo na simulação da concentração de sedimentos em suspensão para o intervalo de tempo horário. Além das simulações da vazão e produção de sedimentos, foi possível detectar os principais processos que afetam os processos hidrossedimentológicos nas diferentes escalas temporais e bacias hidrográficas. Pesquisas adicionais com um maior período de monitoramento utilizado nas simulações podem favorecer o entendimento das mudanças temporais de uso e manejo nessas bacias.

A associação das três abordagens de práticas de conservação do solo e da água foi o melhor cenário para a redução da produção de sedimentos e otimização dos componentes do balanço hídrico, como o escoamento superficial e de base, percolação e recarga do aquífero. Por outro lado, a implementação da prática individual de rotação de culturas e plantas de cobertura conseguiu reduzir significativamente a produção de sedimentos em ambas as bacias hidrográficas agrícolas.

De maneira geral, o estudo conseguiu alcançar os objetivos propostos e, além disso, poderá dar subsídios para futuros estudos em monitoramento e modelagem de bacias hidrográficas, e na implementação de práticas agrícolas sustentáveis.

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