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MODELAGEM DO ESCOAMENTO, DA PRODUÇÃO DE SEDIMENTOS E DA TRANSFERÊNCIA DE FÓSFORO EM BACIA RURAL NO SUL DO BRASIL

TESE DE DOUTORADO

Nadia Bernardi Bonumá

Santa Maria, RS, Brasil
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MODELAGEM DO ESCOAMENTO, DA PRODUÇÃO DE SEDIMENTOS E DA TRANSFERÊNCIA DE FÓSFORO EM BACIA RURAL NO SUL DO BRASIL

Nadia Bernardi Bonumá

Tese apresentada ao Curso de Doutorado do Programa de
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Orientador: Prof. José Miguel Reichert, PhD

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Universidade Federal de Santa Maria
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A Comissão Examinadora, abaixo assinada,
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elaborada por
Nadia Bernardi Bonumá

como requisito parcial para obtenção do grau de
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Santa Maria, 1 de março de 2011.

“We still talk in terms of conquest.
We still haven’t become mature
enough to think in terms of
ourselves as a tiny part of a vast
and incredible universe.”
(Rachel Carson)

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RESUMO

Tese de Doutorado
Programa de Pós-Graduação em Ciência do Solo
Universidade Federal de Santa Maria, RS, Brasil

MODELAGEM DO ESCOAMENTO, DA PRODUÇÃO DE SEDIMENTOS E DA TRANSFERÊNCIA DE FÓSFORO EM BACIA RURAL NO SUL DO BRASIL

AUTORA: NADIA BERNARDI BONUMÁ
ORIENTADOR: PROF. JOSÉ MIGUEL REICHERT
Data e Local da Defesa: Santa Maria, 1 de março de 2011.

Áreas com culturas de tabaco cultivadas intensivamente, no sul do Brasil, vêm afetando a qualidade da água e aumentando a erosão do solo nesta região. A aplicação de grandes quantidades de fertilizantes minerais, maiores do que a exigência da cultura, contribui para a excessiva carga de fósforo nos solos e corpos d'água. A avaliação dos impactos potenciais das mudanças no uso e manejo do solo é fundamental para propiciar uma gestão sustentável dos recursos naturais como solo e água. Neste estudo foram avaliados os processos hidrológicos, a produção de sedimentos e a transferência de fósforo na bacia hidrográfica do Arroio Lino, por meio do modelo *Soil and Water Assessment Tool* (SWAT). A pequena bacia (4,18 km^2) localiza-se no sul do Brasil e seu principal uso da terra é a cultura de fumo sob plantio convencional. As vazões e a produção de sedimentos medidos no exutório da bacia foram utilizadas para análise de sensibilidade, calibração e validação dos parâmetros do modelo. Cargas de fósforo em quatro sub-bacias (A1, A2, B, C) e no exutório foram utilizados para a análise de sensibilidade e calibração do modelo. A análise de sensibilidade foi feita com o uso de um algoritmo que combina as técnicas de Hipercubo Latino (LH) e *One-factor-At-a-Time* (OAT). A calibração foi realizada com o algoritmo *Shuffled Complex Evolution* (SCE-UA). Análises gráficas e medidas estatísticas foram utilizadas para verificar as previsões do modelo. Adaptações nos parâmetros do modelo foram feitas durante as etapas de calibração e validação, tendo em vista a realidade da região em que a bacia está localizada. Na simulação de vazões mensais obtiveram-se valores do índice de eficiência de Nash e Sutcliffe (NSE) de 0,87 na calibração e 0,76 na validação. Com o intuito de representar melhor os processos de deposição de sedimentos nas encostas, o modelo SWAT foi modificado com a incorporação de um termo de capacidade de transporte de sedimentos na paisagem. Com a nova rotina de sedimentos obteve-se um melhor desempenho durante a calibração (NSE de 0,70) em relação ao modelo SWAT original (NSE de -0,14). As simulações com o modelo modificado foram satisfatórias para o transporte de sedimentos em diferentes posições da paisagem. Os resultados sugerem que a integração da rotina de deposição de sedimentos no SWAT aumenta a precisão do modelo de previsões em áreas mais íngremes e, ao mesmo tempo, melhora significativamente a capacidade de prever a distribuição espacial das áreas de deposição de sedimentos. As previsões de cargas de fósforo foram na ordem de grandeza das cargas medidas; no entanto, o modelo não conseguiu prever satisfatoriamente as cargas de fósforo em três sub-bacias (A1, A2 e B). Apesar das lavouras ocuparem apenas 29% da área total da bacia, de acordo com a simulação elas são a principal fonte de nutrientes na bacia hidrográfica (80%). Após a calibração da vazão, da produção de sedimentos e de fósforo, foi realizada a simulação de cenários de manejo do solo na bacia hidrográfica do Arroio Lino. Três cenários de práticas de manejo: preparo convencional (PC), cultivo mínimo (CM) e plantio direto de cultivo (NT) com redução de 50% da taxa de aplicação de fertilizantes foram testados durante um período de 30 anos. A prática de plantio direto não afetou significativamente o escoamento, no entanto afetou fortemente a produção de sedimentos devido à redução da erosão do solo. Houve redução das perdas de fósforo principalmente devido à redução das doses de fertilizantes. Os resultados indicam que as práticas de preparo convencional do solo deveriam ser substituídas por práticas de cultivo mínimo ou direto, a fim de minimizar os impactos ambientais causados por um determinado uso do solo.

Palavras- chave: modelo SWAT, capacidade de transporte de sedimentos, cenários de manejo do solo.

ABSTRACT

Doctor Science Thesis
Graduate Program in Soil Science
Federal University of Santa Maria

MODELING OF WATER, SEDIMENT AND PHOSPHORUS LOADS IN AN AGRICULTURAL WATERSHED IN SOUTHERN BRAZIL

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Defense Place and Date: Santa Maria, March 1st, 2011.

Areas under intensive tobacco crop cultivation have been impacting the water balance and increasing soil erosion in Southern Brazil. Application of large amounts of mineral fertilizers, higher than the tobacco requirement, contributes to excessive phosphorus loads in soil and water bodies. The assessment of potential environmental impacts due to changes in land use and management practices is necessary to achieve the sustainable management of natural resources such as soil and water. In this study the hydrological processes, the sediment yield and the phosphorus transfer in the Arroio Lino watershed were evaluated by using the Soil and Water Assessment Tool (SWAT) model. The small watershed (4.18 km^2) is located in Southern Brazil and its main land use is tobacco crop under conventional tillage. Measured streamflow and sediment yield at the watershed outlet were used for model streamflow sensitivity analysis, calibration and validation. Phosphorus loads at four sub-watersheds (A1, A2, B, C) and at the watershed outlet were used for model sensitivity analysis and calibration. A Latin Hypercube (LH) and One-factor-At-a-Time (OAT) sensitivity analysis was performed on input variables. Model calibration was performed with the Shuffled Complex Evolution Algorithm-Uncertainty Analysis (SCE-UA). Time series plots and standard statistical measures were used to verify model predictions. Adaptations of the model parameters for the reality of the region in which the watershed is located were made during the calibration and validation of the model. The predicted monthly streamflow matched the observed values, with a Nash–Sutcliffe coefficient (NSE) of 0.87 for calibration and 0.76 for validation. In an attempt to account for sediment transport and deposition processes across the landscape, the SWAT model was modified to simulate landscape sediment transport capacity. The new deposition routine performed better during calibration (NSE of 0.70) than SWAT standard version (NSE of -0.14) in the studied watershed. The modified model provided reasonable simulations of sediment transport across the landscape positions. The results suggest that the integration of the sediment deposition routine in SWAT increases model predictions accuracy in steeper areas, while at the same time significantly improves the ability to predict spatial distribution of sediment deposition areas. The predicted P loads are in the order of magnitude of the measured ones, however, the model failed to predict the P loads in three sub-watersheds (A1, A2 and B). Although occupying only 29% of the total land cover, cropland is the primary source of nutrients in the watershed (80%). After calibration of streamflow, sediment yield and phosphorus loads, the simulation of distinct management scenarios was done for the Arroio Lino watershed. Three scenarios of management practices: conventional tillage (CT), minimum tillage (MT) and no-tillage cultivation (NT) with reduction of 50% of fertilizer rate application were tested over a period of 30 years. No-tillage practices did not significantly affect water yield, but greatly affected sediment yield due to reduction of soil erosion. The soluble phosphorus losses decreased mainly when the fertilizer doses decreased. The simulation results suggest that conventional tillage practices should be replaced by less intensive tillage practices in order to minimize environmental impacts caused by a single land use.

Key words: SWAT model, sediment transport capacity, management scenarios.

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LIST OF ABBREVIATIONS

ANA	Brazilian National Water Agency (*Agência Nacional de Águas*)
ARS	U.S. Agricultural Research Service
CONAMA	Brazilian National Environment Council (*Conselho Nacional do Meio Ambiente*)
CNPq	Brazilian National Council for Scientific and Technological Development (*Conselho Nacional de Desenvolvimento Científico e Tecnológico*)
CREAMS	Chemicals, Runoff, and Erosion from Agricultural Management Systems
DEM	Digital Elevation Model
EPA	U.S. Environmental Protection Agency
EPIC	Erosion Productivity Impact Calculator
GIS	Geographic Information System
GLEAMS	Groundwater Loading Effects on Agricultural Management Systems
GOPC	Grid Oriented Phosphorus Component
GPS	Global Positioning System
HSPF	Hydrological Simulation Program–FORTRAN
HRU	Hydrologic Response Unit
INMET	Brazilian National Institute of Meteorology (*Instituto Nacional de Meteorologia*)
LH	Latin Hypercube
MUSLE	Modified Universal Soil Loss Equation
NSE	Nash-Sutcliffe efficiency
OAT	One Factor-At-a Time
RMSE	Root Mean Square Error
ROTO	Routing Outputs to Outlet
RS	*Rio Grande do Sul* state
R^2	Coefficient of determination
SCE-UA	Shuffled Complex Evolution
SD	Standard deviation
SCS	Soil Conservation Service
SHETRAN	Systeme Hydrologique Europeen TRANsport
SWAT	Soil and Water Assessment Tool
SWRRB	Simulator for Water Resources in Rural Basins
UFSM	Universidade Federal de Santa Maria
USDA	U.S. Department of Agriculture

CONTENTS

1 - INTRODUCTION

In Southern Brazil there are extensive soil areas of sloping topography with high susceptibility to erosive processes when the vegetation is removed. These areas, whose soils are predominantly shallow and stony, should be reserved for permanent preservation areas. However, contrary to this determination, many of these soils are extensively used and modified by various agricultural activities. The socio-environmental impacts, which resultant from unplanned exploration, are still not well known in these environments, thus these impacts need to be studied to better understand the extent of the effects generated from the soil and water resources degradation. Possibly, the main factor is the inadequacy of land use, which generates and transfers to surface waters the disaggregated sediments, pesticides and nutrients.

The effects of accelerated soil erosion due to agricultural activities cause on-site impacts, consisting of the losses that occur in the agricultural sites, and off-site impacts, *i.e.* losses that occur outside the agricultural land affecting society as a whole.

The on-site impacts imply in the loss of soil, which can cause removal of fertile layer of the soil, reduction of productivity and quality of agricultural crops, loss of nutrients needed for production, infiltration rate reduction and soil water retention capability reduction, deterioration of soil structure and creation of ravines and gullies, which in some cases precludes their use for agriculture.

The off-site impacts result from the excessive sediment yield which may cause the silting of water resources and the release of pollutants into water resources. The sediment transport and deposition in rivers cause the decrease in the channels depth, hampering navigation, enhancing the risk of floods and rising costs of dredging. The accumulation of sediment in reservoirs causes the reduction of storage volume and decrease of its design life, resulting in an increase in the cost of construction of hydraulic structures.

In terms of water quality, the degradation due to erosion and sedimentation takes place through the processes of pollution and eutrophication. The impacts on water quality may be of physical nature such as change in color, flavor, odor, temperature, abrasive power and turbidity; of chemical nature: through diffusion phenomena, mass transfer and biochemical reactions; and of biological nature through the interference in the development of the aquatic fauna and flora. The surface runoff during the transport of sediments and pollutants to the water bodies causes the increase in the water turbidity. Due to the decrease in the light penetration, turbidity reduces the photosynthetic activity of algae and hinders the growth of aquatic species, and causes the degradation of water quality, leading to increased costs in the water treatment for consumption. During the sedimentological processes nutrients that are adsorbed to the sediment are carried away, among which phosphorus stands out and in excess contributes to the eutrophication of water bodies.

For effective erosion control it is necessary to assess the factors responsible for soil and water degradation in the river basin scale. Several studies have been executed in order to understand and clarify the origin of this pollution, using soil erosion and water quality models to analyze the impacts of land use and climate changes on water balance, sediment yield and water quality.

Among the models that have been used for watershed management studies, the Soil and Water Assessment Tool (SWAT, Arnold et al., 1998) stands out. The model is a continuous time model developed to predict the impact of land management practices in watersheds with varying soils, land use and management conditions.

The SWAT model was developed based on an extensive soil database, plants, agricultural management practices and climate data from the United States. The model was originally designed to use easy acquisition information, requiring little or no calibration when used in North American watersheds. However, when applied in regions with poor data and where the characteristics of climate, soils, plants and agricultural management practices differ from the North American reality, it becomes necessary to perform the calibration of the parameters.

One of the biggest challenges is the lack of field data, thus requiring the use of information from the database models which, in turn, was drawn to regions with distinct characteristics found in Brazilian basins.

1.1 - Objectives

The main objective of this study was to evaluate SWAT model's accuracy to simulate the impact of agricultural management on water balance, sediment yield and phosphorus load in the Arroio Lino watershed located in Southern Brazil.

The specific objectives were:

- To assess the hydrological processes, sediment and phosphorus transfer simulations with SWAT model;
- To optimize simulation results by model parameters sensitivity analysis and calibration;
- To improve the sediment simulations by incorporating a sediment deposition routine in the SWAT code;
- To predict surface runoff volume, sediment yield and phosphorus transfer, assuming different scenarios of management practices alternatives.

1.2 - Hypothesis

In order to achieving the goals, the study was conducted based on two hypotheses:

a) As the SWAT simulated results are in the order of magnitude of the measured ones, the model is a promising tool to evaluate hydrology, sediments and nutrients loads for small watersheds;
b) The obtained data from the simulation can be used to predict the sediment yield and the phosphorus transfer caused by the different management systems used. With such, it is possible to correlate soil use with erosion prediction, to prevent damages to the ecosystem, representing an important tool for maintaining an ecologically sustainable environment.

1.3 - Outline

The thesis consists of 7 chapters. Chapter 1 has presented the motivation, objectives and hypothesis of this research. Additionally, Chapter 1 presents a brief overview of this thesis. Literature review which explains some of the methods previously developed and which are related to this thesis constitutes Chapter 2. Chapters 3, 4, 5 and 6 describe the methodology and the results which are presented in the form of scientific articles:

- Article I - "Hydrology Evaluation of the Soil and Water Assessment Tool for a Small Watershed in Southern Brazil."
- Article II – "Integration of a Landscape Sediment Transport Capacity into Soil and Water Assessment Tool Model."
- Article III – "Simulation of Phosphorus Losses from an Intensive Agriculture Watershed."
- Article IV – "Predicting the Impacts of Agricultural Management Practices on Water, Sediments and Phosphorus Loads."

Chapter 7 consists of conclusions and recommendations for future work. This last chapter is followed by bibliography.

2 - LITERATURE REVIEW

2.1 - Soil erosion and sediment delivery

2.1.1 - Soil erosion

Soil erosion is the single most important environmental degradation problem in the developing world, which has far-reaching economic, political, social and environmental implications due to both on-site and off-site damages (Ananda and Herath, 2003).

The agricultural on-site impacts are related to soil degradation, which includes increased bulk density, reduced aggregate stability, and the decline in organic matter and nutrient resulting in a reduction of cultivable soil depth and a decline in soil fertility (Morgan, 2006).

The off-site impacts of upland soil erosion in tropical and subtropical watersheds include siltation, water flow irregularities, reduction of irrigation, water pollution and agrochemical run-off. Sediments may reduce the capacity of reservoirs, adversely affecting irrigated agriculture and hydro-electricity generation (Ananda and Herath, 2003). Sediment is also a pollutant in its own right and, through the chemicals adsorbed to it, may increase the levels of nitrogen and phosphorus in water bodies and result in eutrophication (Morgan, 2006).

Soil water erosion results when soil is exposed to the erosive powers of rainfall energy and flowing water (Haan et al., 1994). Erosion can be classified in rill, interrill (the area between rills), tunnel, gully and stream channel erosion. Interrill erosion process is rainfall dominated, whereas rill erosion is mostly defined by surface runoff. Rills are small concentrations of flowing water that they can be completely removed by normal cultivation methods, whereas gullies cannot be (Aksoy and Kavvas, 2005). Gully erosion is defined as the erosion process whereby runoff water accumulates and often recurs in narrow channels and, over short periods, removes the soil from this narrow area to considerable depths (Poesen et al., 2003). Tunnel erosion may occur in soils with sublayers that have a greater tendency to transport flowing water than does the surface layer (Aksoy and Kavvas, 2005). Stream channels can be sources (stream channel erosion) or sinks of sediments (sedimentation).

Soil erosion is a two-phase process consisting of the detachment of individual particles from the soil mass and their transport by erosive agents such as running water and wind. When sufficient energy is no longer available to transport the particles a third phase, the deposition, occurs (Morgan, 2006).

2.1.2 - Sediment delivery

Typically, only a small portion of the soil eroded from slopes leaves a particular drainage basin on an event or an annual-average time frame (Slattery, 2002).

Total sediment outflow from a watershed per unit time is called sediment yield. It is obtained by multiplying the sediment loss by a delivery ratio (Novotny and Chesters, 1989). The proportion of eroded sediment that exits the drainage basin is called Sediment Delivery Ratio (SDR) (Aksoy and Kavvas, 2005) or in other words is the ratio of the primary erosion rate on hillslopes to the sediment yield at the basin outlet.

Primary erosion hillslope rate is normally estimated using mathematical models and SDR is estimated using empirical relations. SDR equations related the sediment yield to many factors such as drainage area (USDA, 1979), topography and maximum length of a watershed (Renfro, 1975), bifurcation ratio[1] (Roehl, 1962), slope of the main stream channel (Williams and Berndt's, 1972), land use/land cover (runoff curve numbers) (Williams, 1977), texture (Walling, 1983), sediment sources, proximity to the main stream, channel density, and rainfall-runoff factors (Lu et al., 2006).

Sediment delivery can be limited by reducing either the detachment rate or the transport capacity depending on which has a lower value (Aksoy and Kavvas, 2005).

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[1] Ratio of the number of streams of any order to the number of streams of the next higher order.

2.2 - Phosphorus transfers

Phosphorus (P) is an essential nutrient for plants, being one of the most limiting elements for the crops productivity in tropical soils due to its high adsorption capacity to iron oxides and its low availability for plant absorption. According to Gatiboni (2003), this behavior is a consequence of the ability of P in forming high-energy binding compounds with colloids, giving it high stability in the solid phase. Thus, even when the total contents of this element in the soil are high in relation to the amounts required for plants, only a small fraction of it has low binding energy enabling its desorption and availability to plants.

Soil P exists in many different forms or pools, including the inorganic and organic forms, and available and unavailable forms to plants. The forms that are available to plants involve phosphate present in the solution and the one in a labile form in the soil. The unavailable forms include the immobilized P in the organic fraction, the adsorbed P and the P from primary minerals in the soil. According to Rheinheimer et al. (2008), the dynamics of P in the soil is associated with environmental factors that control the activity of microorganisms, which immobilize or liberate the orthophosphate ions and to the physicochemical and mineralogical properties of the soil.

Phosphorus occurs both naturally within the soil and as additions to it in the form of inorganic and organic fertilizers and animal wastes (Quinton et al., 2001). Although P is one of the essential nutrients for all living things, excessive amounts in surface waters may cause excessive growth of aquatic biota. Such accelerated eutrophication may limit water use for drinking, recreation, and industry in water bodies near the source of the excess P as well as at great distances from the P sources (Owens and Shipitalo, 2006).

P transport in and from catchments is controlled by climate, geology, topography, and anthropogenic influences, such as point-source discharges, industrial outfalls, and diffuse agricultural inputs (Perk et al., 2007). However, a large part of the total P load comes from agricultural nonpoint sources (Djodjic et al., 2002).

Runoff and erosion are the overland processes that transport phosphorus. Runoff transports dissolved forms of P, whereas erosion transports sediment-adsorbed P (Wolfe, 2007). As much of the soil P is associated with particle surfaces, soil erosion is likely to be an important mechanism for transporting P from agricultural fields to the aquatic environment (Quinton et al., 2001).

Different fields within a watershed do not contribute equally to P export from the watershed (Djodjic et al., 2002). Areas of active soil erosion and near-stream areas contribute more to P transport from catchments than areas with low sediment transport rates further away from the river network (Perk et al., 2007).

In a watershed, the areas that could contribute to an increase in the concentration of phosphorus in aquatic ecosystems, would be those in which there exists a combination of factors (Lopez et al., 2007), such as: i) rising levels of phosphorus in the soil; ii) increased susceptibility to erosion; iii) greater proximity of watercourses. The possibility of identifying these areas becomes extremely important when developing a diagnostic towards the planning measures for the control of water pollution by agricultural activities.

However, the spatial delimitation of areas that are sources of sediment (Minella et al., 2007) and phosphorus during rainfall events is difficult to be made as it depends on the assessment of factors such as the processes of sediments transfer from the soil to the channel, which are highly variable in space and time (Page et al., 2005).

During the sedimentological processes nutrient exchange across the water-sediment interface occurred. The role of sediments as a source or as a sink of phosphorus is related to the quality and quantity of this nutrient in the sediments and to the processes that affect its equilibrium in the water-sediment interface (Lopez, 1991).

The deposit of sediment within a watershed may give rise to environmental problems where pollutants are associated with sediment are accumulated in sediment deposition sites. Phosphorus accumulation in floodplains by rivers as a consequence of overbank sedimentation, for example, could represent an important source of phosphorus (Walling, 1999).

The P transfer in surface runoff and sediment at watershed scale has been researched by several authors (Dougherty et al., 2004; Gonçalves et al., 2005; Page et al., 2005, Perk et al., 2007, Algoazany et al, 2007; Lopez et al., 2007; Pellegrini et al., 2009). In a study conducted in the Arroio Lino watershed (in Southern Brazil), Gonçalves et al. (2005) evaluated the water quality and correlated the results with the use of nutrients applied in the soil for the cultivation of tobacco (Nicotiana tabacum L.). High levels of phosphorus were found in the water streams and springs. In days of dry weather (baseflow), the average concentration of total phosphorus was 0.17 mg l^{-1} which is higher than the maximum concentration established by CONAMA Resolution 20 (Brasil, 1986)[2]. The authors concluded that the high levels of phosphorus found in the water were consistent with the high availability for this chemical element in the soil.

In another study conducted in the same watershed, Pellegrini et al. (2009) studied the dynamics of phosphorus in watercourses during rainfall events and its relation with the quantity and the physicochemical properties of the sediments. Water collected in areas with greater anthropic activity showed largest concentrations of sediment and phosphorus in all forms, compared to those collected in areas with greater forest cover. Pellegrini et al. (2009) mention that soluble phosphorus concentrations ranged from 0.009 mg l^{-1} in areas with 90% of forest coverage, 0.071 mg l^{-1} in areas with 90% of contribution of crops and conditions of intermediate soil usage, and 0.031 mg l^{-1} in areas with 50% of pastures and forest remnants. According to the authors point sources of pollution significantly change the dynamics of phosphorus, increasing its pollutant potential. For these reasons, sediments eroded from areas with greater anthropic activity have greater potential for eutrophication of surface waters, due to its ability to supporting the growth of aquatic microorganisms in the long-term.

2.3 - Mathemathical models

Mathematical models have been shown to be cost-effective tools for improving our understanding of erosion processes and evaluating possible effects of land use changes on soil erosion and water quality. They can be classified in various ways,

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[2] The Brazilian National Environment Council (CONAMA) Resolution n. 20/1986 established a hierarchical classification of water bodies (Classes Special, 1, 2, and 3) and a set of limiting concentrations of water quality parameters. These water quality standards were revised and a maximum concentration of 0.15 mg P l^{-1} for watercourses classified as Class 3 was established by CONAMA Resolution n. 357/2005 (Brasil, 2005).

but the most useful distinction is between empirical, conceptual and physically based models.

Watersheds, however, are complex systems that combine natural processes including rainfall, evapotranspiration, surface and underground flow with factors relating to human activities such as deforestation, agricultural production and dams construction. Therefore, a complete representation of every process associated with the hydrological cycle, erosion and sedimentation is not possible (Minoti, 2006). Models that include not only the amount of water, but also the sediment yield and water quality in watersheds, should be used in attempting to represent the complexity of these phenomena. Moro (2005) emphasizes the need to know the hydrological model that invariably is part of all models since the sediments and chemical components are transported via water.

2.3.1 - Hydrological modeling

Hydrological modeling is used to predict runoff from land areas, infiltration into soils and percolation into aquifers. Rainfall–runoff models are often used when streamflow gauge data are not available or not reliable, or yet when estimates of the impact that changing land uses and land covers have on the temporal and spatial distribution of runoff are needed (UNESCO, 2005).

Hydrological rainfall-runoff models can be classified in terms of how processes are represented, the time and space scale that are used and what methods of solution to equations are used (Singh, 1995). The main features for distinguishing the approaches are: the nature of basic algorithms (empirical, conceptual or process-based); whether a stochastic or deterministic approach is taken to input or parameter specification; and whether the spatial representation is lumped or distributed.

Many comprehensive spatially distributed hydrologic models have been developed in the past decade due to advances in hydrologic sciences, such as the Geographical Information System (GIS) and remote-sensing (Narasimhan, 2004). A comprehensive review of watershed hydrology models can be found in Singh and Woolhiser (2002).

A review and comparison of mathematical bases of eleven leading watershed-scale hydrologic and nonpoint-source pollution models was conducted by Borah and Bera (2003). These models were: Agricultural NonPoint–Source pollution model or AGNPS (Young et al., 1989), Annualized Agricultural NonPoint Source model or AnnAGNPS (Bingner and Theurer, 2001), Areal Nonpoint Source Watershed Environment Response Simulation or ANSWERS (Beasley et al., 1980), ANSWERS–Continuous (Bouraoui et al., 2002), CASCade of planes in 2–Dimensions or CASC2D (Ogden and Julien, 2002), Dynamic Watershed Simulation Model or DWSM (Borah et al., 2002), Hydrological Simulation Program – Fortran or HSPF (Bicknell et al., 1993), KINematic runoff and EROSion model or KINEROS (Woolhiser et al., 1990), the European Hydrological System model or MIKE SHE (Refsgaard and Storm, 1995), Precipitation–Runoff Modeling System or PRMS (Leavesley et al., 1983), and Soil and Water Assessment Tool or SWAT (Arnold et al., 1998). The authors concluded that SWAT is a promising model for long–term continuous simulations in predominantly agricultural watersheds.

A more recent review and comparison of applications (Borah and Bera, 2004) of SWAT, HSPF and DWSM models indicated that the most promising long-term continuous simulation model was the SWAT model.

2.3.2 - Erosion and sediment transport models

The erosion and sediment transport model algorithms, as the hydrology ones, can be classified in empirical, conceptual or physics based. However, many models are likely to contain a mix of modules from each of these categories. For example, while the rainfall-runoff component of a water quality model may be physics-based or conceptual, empirical relationships may be used to model erosion or sediment transport (Merritt et al., 2003).

For instance the Universal Soil Loss Equation or USLE (Wischmeier and Smith, 1978) is an empirical model world widely used for soil loss estimation. Its modified version (MUSLE, Williams and Berndt, 1977) was developed to compute soil loss for a single storm event. The USLE was also revised (RUSLE) and revisited for improvement (Renard et al., 1997).

The Water Erosion Prediction Project or WEPP (Flanagan and Nearing, 1995) is a physically-based model for predicting soil erosion and sediment delivery from fields, farms, forests, rangelands, construction sites and urban areas. The Limburg Soil Erosion Model or LISEM (de Roo et al., 1996) is a physically-based runoff and erosion model that simulates the spatial effects of rainfall events on small watersheds. The European Soil Erosion Model or EUROSEM (Morgan et al., 1998) is a physically-based model for predicting soil erosion by water from fields and small catchments. The ANSWERS (Beasley, 1980) includes a conceptual hydrological process and a physically-based erosion process.

The SWAT (Arnold et al., 1998) is a watershed scale model developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in complex watersheds with varying soils, land use and management conditions over long periods of time.

A review of modeling approaches used for the prediction of soil erosion in watersheds was made by Zhang et al. (1996). Additionally Merritt et al. (2003) gave one of the most comprehensive reviews of erosion and sediment transport models. Finally, a more recent review of hillslope and watershed scale erosion and sediment transport models can be found in Aksoy and Kavvas (2005).

2.3.3 - Modeling Phosphorus Transport

Because of time and costs involved in assessing P loss, models are often a more efficient and feasible means of evaluation management alternatives (Sharpley, 2007). These models vary from empirical models, including models based on indicators such as the P-Index, used to examine the risk of P transfer to runoff (Djodjic et al., 2002, *Lopes* et al., 2007) or export coefficient models such as the Generalized Watersheds Loading Function (GWLF) model (Haith and Shoemaker, 1987), to conceptual and process based models, such as Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) (Knisel, 1980), AGNPS (Young et al., 1989), ANSWER (Beasley et al., 1980), HSPF (Bicknell et al., 1993), Erosion Productivity Impact Calculator (EPIC) (Sharpley and Williams, 1990), CENTURY (Parton et al., 1993), and SWAT (Arnold et al., 1998).

The process-based models typically involve the numerical solution of a set of equations that are a mathematical representation of processes such as leaching of P, P transport in runoff and sediments, and stream processes that affect P.

The leaching of P involves simulation of the processes of adsorption and desorption that are often collectively described by relating solid-phase (sorbed) P to dissolved P with a variety of nonlinear equations (McGechan and Lewis, 2002). Two of the more common equations are the Freundlich and Lagmuir equations.

The Langmuir adsorption isotherm is perhaps the best known of all isotherms describing adsorption (Langmuir, 1918 apud Barrow, 1983). The theoretical Langmuir isotherm is often used to describe adsorption of a solute from a liquid solution as Eq. (2.1)

$$Q = Q_{\max}\left[k_L C/(1+k_L C)\right] \tag{2.1}$$

where Q is the quantity of P sorbed (mg kg^{-1}), Q_{max} is the maximum amount of P adsorbed to the soil (mg kg^{-1}); k_L is adsorption equilibrium constant (L mg^{-1}); C is the concentration of P in solution (mg L^{-1}).

The general form of Freundlich is

$$Q = k_f C^b \tag{2.2}$$

where Q is the quantity of P sorbed (mg kg^{-1}), C is the concentration of P in solution (mg L^{-1}); and k_f and b are fitting coefficients.

Freundlich and Lagmuir equations have been incorporated into several field-scale models that describe P leaching (Cabrera, 2007). For example HSPF model has the option of using either a linear kinetic relationship or a Freundlich equation (Bicknell et al., 2001).

On the other hand, watershed scale models commonly use a simplified P cycle model developed by Jones et al. (1984) and Sharpley et al. (1984) as the basis for describing P transformations.

Although much progress has been made with P simulation models, inaccurate estimates can be caused in part by incomplete modeling of the mechanisms involved, as well a lag in the incorporation of recent scientific results into models (Cabrera, 2007).

Commonly used computer models like EPIC have not always been appropriately updated to reflect our improved understanding of soil P transformations and transfer to runoff (Vadas et al., 2006).

2.4 - SWAT Model

The Soil and Water Assessment Tool (SWAT; Arnold et al., 1998) model was developed by the United States Department of Agriculture's Agricultural Research Service (USDA-ARS) and the Texas A&M University. According to Neitsch et al. (2005) SWAT can be used to predict long-term impacts of the land management practices on water, sediment and agricultural chemical yields in complex watershed with varying soils, land use, and management conditions.

Applications of SWAT have expanded worldwide over the last years. Most of the applications have been driven in the U.S. and Europe (Gassman et al., 2007). In Brazil some studies were done for the hydrological and sedimentological simulation and delivery of nutrients to springs in rural watersheds, including the assessment of the impact of different agricultural scenarios in the sediment yield and water quality (Baltokoski et al., 2010; Machado and Vettorazzi, 2003; Machado, Vettorazzi and Xavier, 2003; Moro, 2005; Minoti, 2006; Neves et al., 2006; Santos et al., 2010; Uzeika, 2009). An extensive set of SWAT applications can be found in Arnold and Fohrer (2005) and in Gassman et al. (2007).

Two essential components are needed to set up SWAT model: (a) a GIS system to support the storage and display of the relevant maps, and to perform the terrain analysis needed to delineate watersheds, to identify the stream reaches and the associated subbasins, etc., and (b) a component that can generate all the files needed by SWAT, partly from the input maps and analyses, and partly by manual editing (George and Leon, 2007).

SWAT can be set up using the ArcSWAT interface, an upgrade of AVSWAT-X (Di Luzio et al., 2004), a software system that links ArcGIS software and the model. In addition to the ArcSWAT, another interface for the model has been developed using an open source GIS system, the MapWindow SWAT (MWSWAT) (George and Leon, 2007).

Using the GIS interface the watershed delineation is based on D-8 algorithm. This model also incorporates in itself a parameter calculation function (Neitsch et al., 2005). The concept of this method is that each cell in a DEM is assumed to flow to one of the eight neighboring cells according to the direction of steepest slope. SWAT simulates a watershed by dividing it into multiple subbasins, which are further divided into hydrologic response units (HRU's). These HRU's are the product of overlaying soils, land use and slope classes.

Components of SWAT model include: weather, hydrology, soil temperature, plant growth, erosion/sedimentation, nutrients, pesticides, and land management. A detailed theoretical description of SWAT and its major components is documented in Neitsch et al. (2005).

2.4.1 - Hydrologic cycle

Within SWAT the hydrologic cycle is simulated in two phases: land phase and routing phase. The land phase hydrology controls the amount of water, sediment, nutrient and pesticide loadings. The routing phase consists of defining the movement of water, sediments, etc through the channel network of the watershed (Neitsch et al., 2005).

Once SWAT determines the loadings of water, sediments, nutrients and pesticides to the main channel, the loadings are routed through the stream network of the watershed. As water flows downstream, a fraction may be lost due to evaporation and transmission through the bed of the channel. Another potential loss of water is through utilization for agricultural or human purposes. Flow may be supplemented by rainfall directly on the channel and addition of water from point source discharges. Flow is routed through the channel using the variable storage routing method or the Muskingum method.

In large subbasins with a retention time larger than one day, only a portion of the surface runoff and lateral flow will reach the main channel on the day it is generated. SWAT incorporates a storage function to lag a portion of the surface runoff, lateral flow and the nutrients they transport (Neitsch et al., 2005).

2.4.2 - Sediments

After the sediment yield is evaluated using the MUSLE equation, the SWAT model further corrects this value considering snow cover effect and sediment lag in surface runoff. The SWAT model also calculates the contribution of sediment to channel flow from lateral and groundwater sources. Eroded sediment that enters channel flow is simulated in the SWAT model to move downstream by deposition and degradation (Neitsch et al., 2005).

2.4.3 - Nutrients

The transport of nutrients in the watershed depends on the transformations the compounds undergo in the soil environment. SWAT models the nutrient cycles for nitrogen (N) and phosphorus (P).

2.4.3.1 Phosphorus

Phosphorus (P) can be added to the soil by fertilizer, manure or residue application. In SWAT, P which is present in the soil through sorption processes is removed from the soil by plant uptake and erosion. Unlike nitrogen which is highly mobile, phosphorus solubility is limited in most environments.

SWAT monitors six different pools of phosphorus in the soil (Figure 2.1). Three pools are inorganic forms of phosphorus while the other three pools are organic forms of phosphorus. Fresh organic P is associated with crop residue and microbial biomass while the active and stable organic P pools are associated with the soil humus. The organic phosphorus associated with humus is partitioned into two pools to account for the variation in availability of humic substances to mineralization. Soil inorganic P is divided into solution, active and stable pools (Neitsch et al., 2005).

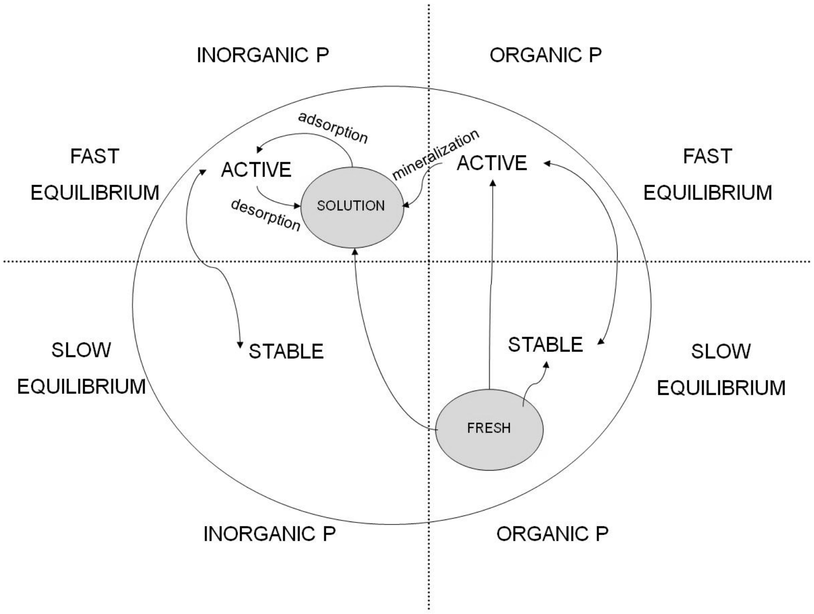

Figure 2.1 – Major components of the P cycle in SWAT model.

The solution P is actually labile P (Chaubey et al., 2007), in conformance with the original EPIC version of the P module as described in Jones et al. (1984) and Sharpley et al. (1984). Labile P was defined by Sharpley et al. (1984) as the P that can be extracted from soil using an anion exchange resin and therefore represents solution P plus weakly sorbed P. Transformations of soil P among these six pools are regulated by algorithms that represent mineralization, decomposition, and immobilization. The labile pool is in rapid equilibrium (several days or weeks) with the active pool. The active pool is in slow equilibrium with the stable pool.

Initial amounts of labile and organic P contained in humic substances for all soil layers can be either specified by the model user or designated with SWAT model default values. The model initially sets concentration of labile P in all layers to 5 mg P kg^{-1} soil for unmanaged land under native vegetation and 25 mg P kg^{-1} soil for cropland conditions (Neitsch et al., 2005; Chaubey et al., 2007).

The active mineral pool P ($P_{active\_mineral\_pool}$) concentration (mg kg^{-1}) is initialized as

$$P_{active\_mineral\_pool} = P_{solution}\left(\frac{1-PAI}{PAI}\right) \tag{2.3}$$

where P solution is the amount of labile P (mg P kg^{-1}) and PAI is the P availability index. PAI, which is also called the P sorption coefficient (PSP) (Radcliff et al., 2009), is estimated using the method outlined by Sharpley et al. (1984).

The stable mineral pool P ($P_{stable\_mineral\_pool}$) concentration (mg P kg^{-1}) is initialized as

$$P_{stable\_\min eral\_pool} = 4(P_{active\_\min eral\_pool}) \tag{2.4}$$

SWAT model makes all nutrient calculations on a mass basis even though all nutrient levels are input in the model as concentrations. The nutrient concentration (mg kg^{-1} or ppm) is converted to mass (kg P ha^{-1}) by multiplying it by the depth of the soil layer and soil bulk density (SOL_BD) and performing appropriate unit conversions.

The inorganic P pool, originating either from mineralization of organic P or P applied directly as inorganic fertilizer, is simulated considering plant uptake and conversion to active and stable forms of inorganic P (Figure 2.1). The movement of P between the labile and active mineral pools is estimated using the following equilibrium equations (Neitsch et al., 2005; Chaubey et al., 2007):

$$P_{soluble/active} = P_{solution} - mineralP_{active}\left(\frac{1-PAI}{PAI}\right)$$

$$\text{if} \quad P_{solution} > mineralP_{active}\left(\frac{1-PAI}{PAI}\right) \tag{2.5}$$

$$P_{soluble/active} = 0.1\left(P_{solution} - mineralP_{active}\left(\frac{1-PAI}{PAI}\right)\right)$$

$$\text{if} \quad P_{solution} < mineralP_{active}\left(\frac{1-PAI}{PAI}\right) \tag{2.6}$$

where $P_{solution/active}$ is the amount of P transferred between the labile and active mineral pool (kg ha^{-1}), $P_{solution}$ is the amount of labile P (kg P ha^{-1}), and PAI is P availability index. A positive value of $P_{solution/active}$ indicates transfer of P from solution to the active mineral pool (adsorption), and a negative value indicates that P is transferred from the active mineral pool to labile pool (desorption). Phosphorus availability index controls the equilibrium between the solution and active mineral pool and specifies what fraction of fertilizer P is in solution after the rapid reaction period.

Vadas et al. (2006) subsequently observed that a constant of 0.1 (equation 2.6) underestimated soil P desorption and suggested a constant of 0.6 be used when the flux is moving in this direction.

In estimating slow sorption of P (where sorbed P is the stable pool), SWAT assumes that the stable mineral pool is four times the size of the active mineral pool. The movement of P between the active and stable pools is calculated using the following equations (Neitsch et al., 2005):

$$P_{active/stable} = \beta_{eqP}(4mineralP_{active} - mineralP_{stable})$$

$$\text{If } mineralP_{stable} < 4mineralP_{active} \qquad (2.7)$$

$$P_{active/stable} = (0.1\beta_{eqP})(4mineralP_{active} - mineralP_{stable})$$

$$\text{If } mineralP_{stable} > 4mineralP_{active} \qquad (2.8)$$

where $P_{active/stable}$ is the amount of P transferred between the active and stable mineral pools (kg P ha^{-1}), and β_{eqP} is the slow equilibrium rate constant (0.0006 d^{-1}). A positive value of $P_{active/stable}$ indicates transfer of P from the active mineral pool to the stable mineral pool, and a negative value indicates transfer of P from the stable mineral pool to the active mineral pool.

Plant use of phosphorus is estimated using the supply and demand approach where the daily plant phosphorus demands are calculated as the difference between the actual concentration of the element in the plant and the optimal concentration.

Soluble phosphorus and organic phosphorus may be removed from the soil via the water fluxes. Because phosphorus is not very soluble, the loss of phosphorus dissolved in surface water is based on the concept of partitioning phosphorus into a solution and a sediment phase. The amount of soluble phosphorus removed in runoff is predicted using labile concentrations in the top 10 mm of the soil, the runoff volume and the partitioning factor (PHOSKD):

$$P_Q = \frac{P_{sol}.ES}{\rho_b.D.k_d} \qquad (2.9)$$

where P_Q is the amount of P transferred between the active and stable mineral pools (kg P ha^{-1}), P_{sol} is the amount of labile P (kg P ha^{-1}), ES is the amount of surface runoff (mm H_2O), ρ_b· is the soil bulk density (mg m^{-3}), D is the depth of the surface layer, and k_d is the P soil partitioning coefficient (m^3 mg^{-1}).

The amount of P transported with sediment to the stream is simulated with a loading function:

$$P_{sed} = 0{,}001.ConcP_{sed}\cdot\left(\frac{SY}{A}.\varepsilon\right) \tag{2.10}$$

where P_{sed} is the amount of phosphorus transported with sediment to the main channel in surface runoff (kg P ha^{-1}), $ConcP_{sed}$ is the concentration of phosphorus attached to sediment in the top 10 mm (g P metric ton $soil^{-1}$), SY is the sediment yield on a given day (metric tons), A is the HRU area (ha), and ε is the phosphorus enrichment ratio.

Additionally, baseflow P concentrations can be set to simulate lateral subsurface flow and ground water contributions to the river loads (Radcliff et al., 2009).

SWAT model users have an option to include or exclude in-stream processes in SWAT simulations. When the in-stream component is included, the model routes the state variables through additional algorithms that have been adapted from QUAL2E, a steady-state stream water-quality model developed by Brown and Barnwell (1987).

2.4.4 - Management Practices

SWAT incorporates detailed information on agricultural and urban land and water management into a simulation. General agricultural management practices include tillage, planting, fertilization, pesticide application, grazing, harvest, kill[3], and filter strips. These management practices are incorporated into the model through various input data and parameters affected by the practices.

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[3] The kill operation represents the end of growing season. During the simulation, it stops plant growth and converts all plant biomass to residue (Neitsch et al., 2005).

2.5 - Model evaluation: Sensitivity analysis, calibration and validation

The ability of a watershed model to sufficiently predict constituent yields and streamflow for a specific application is evaluated through sensitivity analysis, model calibration, and model validation (White and Chaubey, 2005)

A sensitivity analysis can provide a better understanding of which particular input parameters have greater effect on model output (Feyereisen et al., 2007). This analysis may also identify the most sensitive parameters, which ultimately dictate the set of parameters to be used in the subsequent calibration process (Kannan, 2007).

Model calibration is the process of estimating model parameters by comparing model predictions (output) for a given set of assumed conditions with observed data for the same conditions (Moriasi et al., 2007). Calibration should be performed by hierarchical process, beginning with hydrology, followed by sediment, and finally pollutant transport, because errors in the current component will be transferred and magnified in all the following components (Santhi et al., 2001).

Sensitivity, calibration, and uncertainty analyses are vital and interwoven aspects of applying SWAT and other models (Gassman et al., 2007). As SWAT is a complex model with many parameters that can complicate manual model calibration (Green and van Griensven, 2008), complex automated calibration procedures have been successfully used for hydrological modeling with SWAT (Green and van Griensven, 2008; Van Griensven and Bauwens, 2003; Van Griensven and Meixner, 2003; Van Griensven et al., 2006).

Since no simulation model is intended merely to show how well it fits the data used for its development, performance characteristics derived from the calibration data set are insufficient evidence for its satisfactory performance (Klemes, 1986). So the fulfillment of the calibrated model parameter set should be validating against a set of independent measured data.

Validation procedures are similar to calibration procedures in that predicted and measured values are compared to determine if the objective function is met (White and Chaubey, 2005). Good validation results support the usefulness of the model to predict future conditions under alternative land use and management scenarios and future climates.

3 - ARTICLE I: HYDROLOGY EVALUATION OF THE SOIL AND WATER ASSESSMENT TOOL FOR A SMALL WATERSHED IN SOUTHERN BRAZIL

Abstract

Problem statement: Areas under intensive tobacco crop cultivation have been impacting the water balance and have become sources of environmental contamination in Southern Brazil. Correctly determining the area's hydrology is essential since it is the driving force of sediment and nutrient loading dynamics. **Approach:** The Soil and Water Assessment Tool (SWAT) model was used to evaluate hydrological processes for the Arroio Lino watershed, located in Southern Brazil. The observed streamflow at the watershed outlet was used for model streamflow sensitivity analysis, calibration and validation. A Latin Hypercube (LH) and One-factor-At-a-Time (OAT) sensitivity analysis was performed on 27 input variables. Model calibration was performed with the Shuffled Complex Evolution Algorithm-Uncertainty Analysis (SCE-UA). Time series plots and standard statistical measures were used to verify model predictions. **Results:** The most sensitive parameters for runoff were curve number (CN2), soil evaporation compensation factor (ESCO), and baseflow alpha factor (ALPHA_BF). The predicted monthly streamflow matched the observed values, with a Nash–Sutcliffe coefficient of 0.87 during calibration, and 0.76 during validation. The calculated statistics were lower for the daily predictions than the monthly predicted values. **Conclusion/Recommendations:** The results suggest that the SWAT model is a promising tool to evaluate hydrology in Brazilian watersheds, especially on a monthly or annual basis. The calibrated hydrologic model can be used for further analysis of the effect of climate and land use changes, as well as to investigate the effect of different management scenarios on stream water quality.

Keywords: SWAT model; Hydrological process; Agricultural watersheds

3.1 - Introduction

Brazil has one of the world's largest fresh water reserves however it is not distributed equally among regions. When a lack of available fresh water is combined with low income status and a lack of resource management, pollution and environmental degradation can further reduce the amount of potable water. Agricultural lands that are intensively cultivated (i.e. tobacco crop) in Southern Brazil, have been causing changes in the water balance and and have become sources of environmental contamination. Most tobacco in Southern Brazil is produced in small farms on land with low agricultural potential (Merten and Minella, 2006). Due to the shortage of plain areas for cropping, the farmers deforest steep lands to cultivate tobacco under conventional soil tillage (Pellegrini et al., 2009). Steep land, combined with inadequate cultivation practices have caused rapid degradation of natural resources, contributing to a worsening of the cycle of poverty (Merten and Minella, 2006). Incompatible agricultural practices with the land use capability of these regions and the application of high fertilizer and pesticide rates make tobacco cultivation an activity with a high contamination risk for water resources in watersheds (Kaiser et al., 2010).

In search of solutions for a better utilization of water resources, the assessment of water quality and quantity become increasingly important. To adequately assess these components an understanding of hydrologic processes is critical. A key hydrological factor is surface runoff, which is primarily responsible for the transport of sediment, nutrients, and other contaminants throughout the watershed. However, long-term watershed monitoring data are rare due to the expenses involved (Santhi et al., 2006), and, consequently, the lack of streamflow measurements complicates this water availability evaluation.

Computer-based watershed models can save time and money because of their ability to perform long-term simulation of the effects of watershed processes and management activities on water quality, water quantity, and soil quality (Moriasi et al., 2007). The ability of a watershed model to sufficiently predict constituent yields and streamflow for a specific application is evaluated through sensitivity analysis, model calibration, and model validation (White and Chaubey, 2005)

Among the many hydrologic models developed in the past decades stands the Soil and Water Assessment Tool (SWAT, Arnold et al., 1998), developed by the United States Department of Agriculture's Agricultural Research Service (USDA-ARS) and the Texas A&M University. SWAT is a continuous time model developed to predict the impact of land management practices in watersheds with varying soils, land use and management conditions. The model is physically and empirically based, uses readily available inputs, is computationally efficient and enables users to study long-term impacts (Neitsch et al., 2005). A detailed theoretical description of SWAT and its major components is documented in Neitsch et al. (2005). An extensive set of SWAT applications can be found in Arnold and Fohrer (2005) and in Gassman et al. (2007).

Applications of SWAT have recently expanded worldwide. Most of the applications have occurred in the U.S. and Europe (Gassman et al., 2007). Only a few peer-reviewed articles about SWAT applications in developing countries have been published, such as Baltokoski et al. (2010) (Brazil), Mishra et al. (2007) (India), Ouyang et al. (2008) (China), Schuol et al. (2008) (Africa), Setegn et al. (2010) (Africa), Von Stackelberg et al. (2007) (Uruguay), Wu and Chen (2009) (China), and Yang et al. 2008 (China).

The focus of this study is to assess the ability of the Soil and Water Assessment Tool (SWAT) to simulate streamflow for a small watershed in Southern Brazil. The research results may be applicable to other watersheds in the same region. Thus, the objectives of this study are to (1) conduct parameter sensitivity analysis; (2) calibrate and validate the SWAT model for streamflow at the watershed outlet; and (3) evaluate the simulated water balance for the entire watershed.

3.2 - Materials and Methods

3.2.1 - SWAT model

Components of SWAT model include: weather, hydrology, soil temperature, plant growth, erosion/sedimentation, nutrients, pesticides, and land management. In this study, we focused mainly on the hydrologic component of the model.

SWAT simulates a watershed by dividing it into multiple subbasins, which are further divided into hydrologic response units (HRU's). These HRU's are the product of overlaying soils, land use and slope classes. The water balance in each HRU is composed by four storage volumes: snow, soil profile, shallow aquifer, and deep aquifer.

Major hydrology components of SWAT include: precipitation, interception, evapotranspiration, infiltration, percolation, and runoff. The SWAT model uses two phases of the hydrologic cycle, one for the land processes and other for the channel processes. The land phase of the hydrologic cycle is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} (PREC - SURQ - ET - PERCO - BF) \tag{1}$$

where SW_t is the final soil water content (mm), SW_0 is the soil water content available for plant uptake (initial water content - permanent wilting point water content), t is the time in days, $PREC$ is the amount of precipitation (mm), $SURQ$ is the amount of surface runoff (mm), ET is the amount of evapotranspiration (mm), $PERCO$ is the amount of percolation (mm), and BF is the amount of baseflow (mm).

The actual plant transpiration and the actual soil evaporation are estimated based on the potential evapotranspiration and additional soil and landuse parameters. SWAT offers three methods to estimate the potential evapotranspiration: Priestley-Taylor (Priestley and Taylor, 1972), Hargreaves (Hargreaves and Samani, 1985), and Penman-Monteith (Allen et al., 1989). For this study, the Penman-Monteith method was used.

In SWAT the surface runoff can be estimated from daily or sub-daily rainfall. In this study, the surface runoff was estimated from daily rainfall with the modified Soil Conservation Service (SCS) curve number method (Mishra and Singh, 2003). The SCS curve number parameter (CN2) is a function of the land use, soil's permeability and antecedent moisture conditions. Peak runoff rate predictions are made with a modification from the rational method. Channel routing can be simulated using either the variable-storage method or the Muskingum method. The variable-storage method was used in this study.

Two essential components are needed to set up SWAT model: (a) a GIS system to support the storage and display of relevant maps, to perform the terrain analysis needed to delineate watersheds, and to identify the stream reaches and their respective subbasins, and (b) a component that can generate all the files needed by SWAT, partly from the input maps and analyses, and partly by manual editing (George and Leon, 2007).

The SWAT model can be set up using the ArcSWAT interface, an upgrade of AVSWAT-X-X (Di Luzio et al., 2004), a software system that links ArcGIS software and the model. In addition to ArcSWAT, another interface for the model has been developed using an open source GIS system, MapWindow SWAT (MWSWAT) (George and Leon, 2007).

3.2.2 - Watershed description

The Arroio Lino watershed covers 4.8 km^2 and is located in Agudo County, in the state of Rio Grande do Sul, Brazil (29.1° S, 67.1° E) (Figure 3.1). The Arroio Lino is a tributary of the Jacuí River, where the drainage area is characterized by intensive land use for agriculture and livestock.

Concerning the geological aspects, the watershed belongs to the "Serra Geral Formation" which presents basaltic hillsides and localized outcrops of Botucatu sandstone (Pellegrini et al., 2009). Due to the steep terrain, geologic structure, and rock units, the drainage patterns progress over steep slopes. *Chernossolos* (Mollisols) predominate, but *Neossolos* (Entisols) are found on steeper slopes

(USDA, 1999; Dalmolin et al., 2004). The vegetation is composed by remnants of seasonally deciduous forests in different stages of succession (Pellegrini et al., 2009).

Climate in the region is humid subtropical (Cfa type), according to the Köppen classification, with an average temperature of more than 22 ℃ in the hottest and between -3 and 18 ℃ in the coldest month. Rains are usually well distributed, ranging from 1,300 to 1,800 mm year^{-1} (Kaiser et al., 2010).

Almost 30% of the Arroio Lino watershed area is occupied by annual crops and more than 50% by native forest cover. Approximately 90% of the crops areas are devoted to tobacco production (Pellegrini et al., 2009). The tobacco crops are cultivated under conventional tillage, with environmental degradation due to intense agricultural exploration.

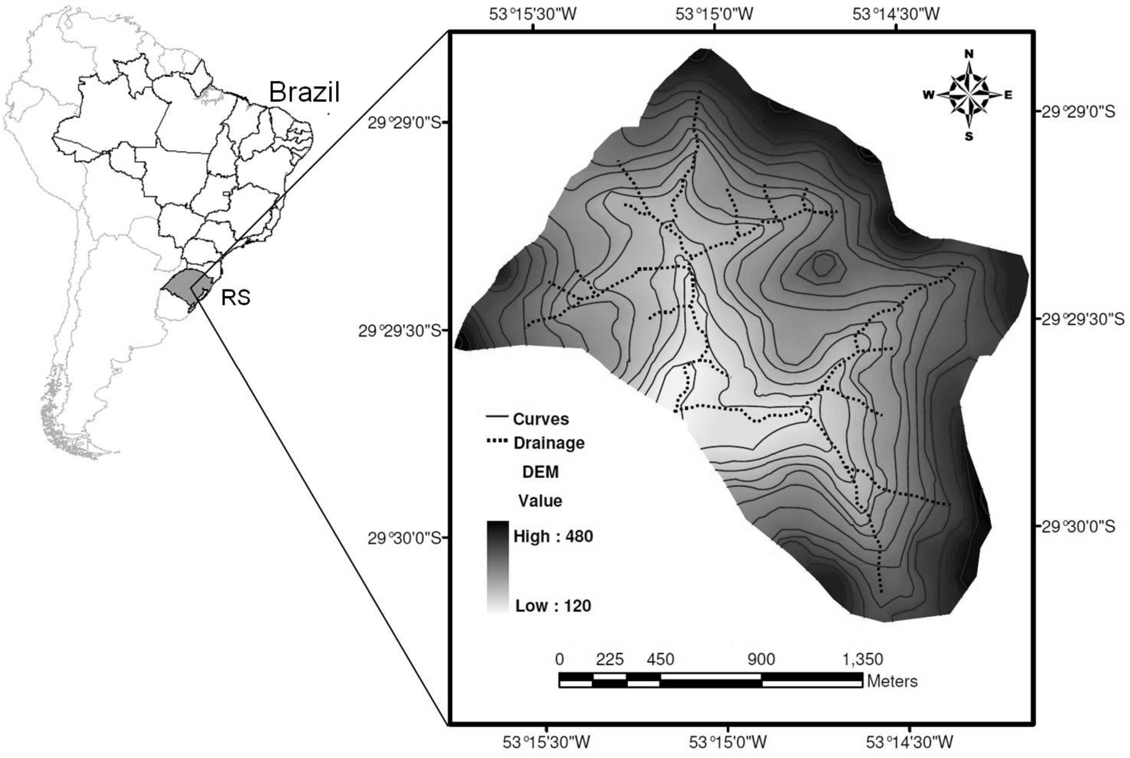

Figure 3.1 – Location of the Arroio Lino Watershed in Rio Grande do Sul (RS) state in Brazil.

3.2.3 - Input data

The SWAT model requires topography, land use, management, soil parameters input, and weather data. The digital maps (topography, land use, slopes, and soil types) were processed with a GIS preprocessing interface to create the required model input files.

Topographic Data. Topographic data were obtained by digitizing contour lines and drainage network from a 1:25,000 scale topographic map. The digitized contour vectors were used to create Triangular Irregular Network (TIN) for generating the Digital Elevation Model (DEM) with spatial pixel resolution of 10 m (Figure 3.1). The DEM and the digitized drainage network were used to delineate and partition the watershed into 21 sub-watersheds and reaches with an average size of 0.15 km^2 (3% of the watershed area). Jha et al. (2004) examined the effect of basin subdivision on simulation results and they suggest that the optimal size of sub-watersheds is 2–6% of the simulated area. The slope map was divided in five slope classes: 0-5%, 5-15%, 15-30%, 30-45%, and >45%. Information extracted and calculated from the DEM includes overland slope, slope length, and elevation corrections for precipitation and evapotranspiration.

Land Use and Agricultural Management Data. Land use was determined by field surveys, assisted by a geographic positioning system (GPS) with a GIS software (Pellegrini et al., 2009). The main land uses in the watershed consist of cultivated tobacco fields, forest, pasture and fallow. A detailed list of agricultural management operations carried out in the watershed with dates and type of operation (planting of crop, tillage, and harvest) was created. In SWAT, the SCS curve number parameter (CN2) is updated for each management operation. The date of operation can vary per year depending on the cumulative days exceeding the minimum (base) temperature for plant growth. The potential heat units for the crops were calculated and the values were added to the management input file (.mgt file).

Soil Data. The digital soil map (1:15,000) identifies 11 soil types, mainly Entisols and Mollisols (Dalmolin et al., 2004; USDA, 2003). The key soil physical properties such as texture percentage (i.e. sand, silt and clay), bulk density, porosity and water content at different tension values (available water capacity) were analyzed for each soil. Additional soil parameters were taken from previous studies developed in the watershed (Rheinheimer, 2003) and assigned to main soil types. The soils information were added in the SWAT user soils databases (.usersoil file).

Hydrologic response units (HRU's). The number of HRU's is limited by the precision of the input digital maps. A realistic combination of land uses, soil types and slope classes, with a 10% threshold area resulted in 344 HRU's.

Weather data. Rainfall data were obtained from an automatic meteorological station and from five rain gauges installed within the watershed (Kaiser et al., 2010; Sequinatto, 2007). Rainfall data for the watershed were collected from 2001 to 2005. The Penman-Monteith potential evapotranspiration method was used in this study and requires solar radiation, air temperature, wind speed, and relative humidity as input. Daily maximum and minimum temperature, solar radiation, wind speed and humidity values were also obtained from the automatic meteorological station. The gaps in the climate data were completed with information from the Brazilian National Institute of Meteorology (INMET) and National Water Agency (ANA) stations adjacent to the watershed.

Hydrologic Discharge Data. A Parshall flume at the watershed outlet was established in 2003 to collect stage heights in 10-minute intervals using an automatic water level sensor (Gonçalves et al., 2005; Sequinatto, 2007). Flow rates were calculated with a stage-discharge relationship that was developed using in-situ manual velocity measurements at the stream cross section where the water level sensor is located (Sequinatto, 2007). The 10-minute flow rates were integrated to obtain daily outflow rates. Daily streamflow data at the watershed outlet were used for model sensitivity analysis, calibration and validation.

3.2.4 - Model evaluation

SWAT performance was evaluated using graphical comparison and statistical analysis to determine the quality and reliability of the predictions when compared to measured values. Summary statistics include the mean and standard deviation (SD), where the SD is used to assess data variability. The goodness-of-fit measures were the coefficient of determination (r^2) and the Nash-Sutcliffe efficiency (NSE) value (Nash and Sutcliffe, 1970).

The coefficient of determination (r^2) is calculated as:

$$r^2 = \frac{\left(\sum_{i=1}^{n}(Y_i^{obs} - Y_m^{obs})(Y_i^{sim} - Y_m^{sim})\right)^2}{\sum_{i=1}^{n}(Y_i^{obs} - Y_m^{obs})^2 \sum_{i=1}^{n}(Y_i^{sim} - Y_m^{sim})^2} \tag{2}$$

where n is the number of observations during the simulated period, Y_i^{obs} and Y_i^{sim} are the observed and predicted values at each comparison point i, and Y_m^{obs} and Y_m^{sim} are the arithmetic mean of the observed values. The r^2 ranges from 0 to 1, with higher values indicating less error variance.

Nash-Sutcliffe efficiency (NSE) is calculated as:

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

NSE ranges between -∞ and 1.0, where a value of 1 indicates a perfect fit. The NSE value describes the amount of variance for the observed values over time that is accounted for by the model.

Further goodness-of-fit was quantified using the percent bias (PBIAS) and the ratio of the root mean square error to the standard deviation of measured data (RSR) (Moriasi et al., 2007). PBIAS assesses the average tendency of simulated data to exhibit underestimation (positive PBIAS values) or overestimation (negative PBIAS values) bias (Gupta et al. 1999):

$$PBIAS = \frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim}) * 100}{\sum_{i=1}^{n} Y_i^{obs}} \tag{4}$$

where PBIAS is the deviation of simulated values (Y^{sim}) relative to measured values (Y^{obs}), expressed as a percentage.

RSR incorporates the benefits of error index statistics and includes a normalization factor, so that the resulting statistic and reported values can be applied to various constituents. RSR is calculated as the ratio of the root mean square error and standard deviation of measured data (equation 4; Moriasi et al., 2007):

$$RSR = \frac{RMSE}{SD_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}(Y_i^{obs} - Y_m^{obs})^2}\right]} \tag{5}$$

where RMSE is the root mean square error and SD_{obs} is the standard deviation of measured values. RSR varies from the optimal value of 0, which indicates zero RMSE or residual variation and therefore perfect model simulation, to a large positive value. The lower RSR, the lower is the RMSE, and the better is the model simulation performance (Moriasi et al., 2007).

In order to assess how well the model performed, Green et al. (2006), Green and van Griensven (2008) and Wu and Chen (2009) used standards of NSE > 0.4 and $r^2 > 0.5$. Santhi et al. (2001) assumed monthly NSE > 0.5 and $r^2 > 0.6$ indicated acceptable model performance when calibrating for hydrology. Moriasi et al. (2007) suggested that model simulation can be judged as satisfactory if NSE > 0.50 and RSR ≤ 0.70, and if PBIAS ± 25% for streamflow for a monthly time step. For this study, $r^2 > 0.6$, NSE > 0.50, RSR ≤ 0.70, and PBIAS ± 25% were chosen as standards for acceptable simulations. Nevertheless, when watershed models are evaluated on a daily time step the ratings can be less strict than for longer time steps (Moriasi et al., 2007).

- Parameter Sensitivity Analysis.

In order to analyze the effect of model parameters on model output directly and on model performance a parameter sensitivity analysis tool embedded in SWAT was used (van Griensven et al., 2006). The errors on the output were evaluated by comparing the model output to corresponding observations. The relative ranking of which parameters most affect the output was determined by error functions that were calculated for the daily flow measured in the watershed outlet gauge.

- Calibration and validation.

Measured data from the watershed outlet gauge were compared to SWAT output during calibration and validation. Predicted total flow for monthly and daily calibration and validation was calculated from the FLOW_OUT model output for the appropriate subbasin in the main channel output file from SWAT (output.rch file). To calibrate the streamflow an automated digital filter technique (Arnold and Allen, 1999) was used to separate baseflow from the measured streamflow. Baseflow is an important component of the streamflow and had to be calibrated before the model was fully calibrated for streamflow and other components (Jha, Gassman and Arnold, 2007). As SWAT is a complex model with many parameters that will complicate manual model calibration, an auto-calibration procedure tool that is embedded in SWAT was also used. This procedure is based on a multi-objective calibration and incorporates the Shuffled Complex Evolution Method algorithms (SCE-UA). The optimization uses a global optimization criterion through which multiple output parameters can be simultaneously evaluated (van Griensven et al., 2002). The calibration procedure followed the steps presented in Green and van Griensven (2008). First the parameters were manually calibrated until the model simulation results were acceptable as per the NSE, r^2, RSR and PBIAS values. Next, the final parameter values that were manually calibrated were used as the initial values for the autocalibration procedure. Maximum and minimum parameter value limits were used to keep the output values within a reasonable value range. Finally, the autocalibration tool was run with the optimal fit values to provide the best fit between the measured and simulated data as determined by the NSE values and how reasonable the values are. The autocalibrated determined parameter values were then adjusted to ensure that they were reasonable. For the validation the model was running using input parameters determined during the calibration process for other time period.

3.3 - Results and Discussion

3.3.1 - Hydrology parameters sensitivity analysis

Sensitivity analysis was carried out using 27 parameters of SWAT model suggested as being the most sensitive for the simulation of the streamflow (van Griensven et al., 2006). Regarding the effects on variable flow of the 27 parameters, 20 showed some sensitivity (Table 3.1). The lack of effect of the other seven parameters lies in the fact that most of them are directly related to the processes of melting snow, which do not occurred in the area.

Table 3.1 - Sensitive model parameters for streamflow.

Parameter	Description	Rank
ALPHA_BF	Baseflow alpha factor (days)	3
BIOMIX	Biological mixing efficiency	20
BLAI	Potential maximum leaf area index for the plant	5
CANMX	Maximum amount of water that can be trapped in the canopy when the canopy is fully developed (mm)	8
CH_K2	Effective hydraulic conductivity (mm h^{-1})	4
CH_N2	Manning's roughness coefficient for the channel	12
CN2	Initial SCS runoff curve number for moisture condition II	1
EPCO	Plant evaporation compensation factor	14
ESCO	Soil evaporation compensation factor	2
GW_DELAY	Groundwater delay time (days)	16
GW_REVAP	Groundwater re-evaporation coefficient	17
GWQMN	Minimum shallow aquifer depth for "revap" to occur (mm)	6
REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	15
SLOPE	Average slope steepness (m m^{-1})	9
SLSUBBSN	Average slope length (m)	19
SOL_ALB	Soil albedo	18
SOL_AWC	Available water capacity of the soil (mm H_2O mm $soil^{-1}$)	10
SOL_K	Saturated hydraulic conductivity of the soil (mm h^{-1})	7
SOL_Z	Soil depth (mm)	11
SURLAG	Surface runoff lag coefficient	13

The parameter whose variation had the highest sensitivity was the initial SCS Curve Number II value (CN2). The CN2 is a key parameter of the SCS method; increased values of CN2 imply an increase in the surface runoff. The second parameter with the greatest effect was the soil evaporation compensation factor (ESCO); Kannan et al. (2007) noticed that a change in the value of the ESCO affects all the water balance components. The third most sensitive parameter was the baseflow alpha factor (ALPHA_BF). Similar analysis made in other watersheds suggested that the parameters CN2 and ALPHA_BF also have great importance in the simulation of water quality (van Griensven et al., 2006).

3.3.2 - Calibration and Validation

Simulation was carried out from January 1, 2001 to December 31, 2005. The period from January 1, 2001 to December 31, 2003 serves as a warm-up period for the model. The warm-up period was used to establish appropriate initial conditions for soil water storage. The outlet gauge data from January to December 2005 were used to optimize the calibration parameters and the remaining data for validation.

The uncalibrated SWAT run showed clear faults in the ability to describe measured processes. Simulation using default values parameters underestimated streamflow in relation to the measured streamflow, particularly during austral spring months (September to December). Both manual and auto-calibration procedures were required to correct these simulation errors. To calibrate and validate base and surface runoff flows, total flow was separated into two components. An automated digital filter technique (Arnold and Allen, 1999) was used to separate baseflow from the measured total flow. Values of rainfall as well as total flow and baseflow estimated with the digital filter for the period of 2004-2005 are presented in Figure 3.2.

The simulated surface flow was increased through calibration of the following parameters: runoff curve number (CN2), daily curve number calculation method (ICN), curve number coefficient (CNCOEF), soil evaporation compensation factor (ESCO), initial soil water content expressed as a fraction of field capacity (FFCB), and available soil water capacity (SOL_AWC). The Soil Conservation Service runoff curve number for moisture condition II (CN2) parameter was originally set to values recommended by the USDA SCS National Engineering Handbook (USDA, 1972) for each hydrologic group. For estimation of CN2 to slopes above 5%, an equation developed by Williams (1995) was used. The final CN2 values were kept within reasonable ranges by limiting the change from the original value to + 10%. The ICN and curve number coefficient (CNCOEF) parameters are defined in Williams and LaSeuer (1976) and Green et al. (2006). The ICN and CNCOEF parameters were used to account for the soil moisture in addition to the SCS runoff curve number (Green et al., 2008). The soil evaporation compensation factor (ESCO) is a calibration parameter and not a property that can be directly measured. As ESCO increases, the depth to which soil evaporative demand can be met decreases, which limits soil evaporation and reduces the simulated value for ET (Feyereisen, 2007). The soil evaporation compensation factor (ESCO) was adjusted so as to decrease actual evapotranspiration. The initial soil water content was chosen to be expressed as a fraction of field capacity (FFCB=1.0) instead of be expressed as a function of average annual precipitation (FFCB=0.0). The available soil water capacity (SOL_AWC) was reduced which resulted in an increase in surface flow. Stormflow is inversely proportional to SOL_AWC; the two variables exhibit a straight-line relationship throughout the range of values for SOL_AWC. Reducing SOL_AWC results in the soil profile filling sooner, with more runoff, less ET, and increased baseflow (Feyereisen, 2007).

As the values of baseflow simulated with SWAT was significantly lower in relation to the baseflow estimated from the measured streamflow, groundwater parameters were adjusted to improve the subsurface response. The threshold depth of water in the shallow aquifer for "revap" to occur (REVAPMN) was increased and the time for water leaving the bottom of the root zone to reach the shallow aquifer (GW_Delay) was reduced. Saturated hydraulic conductivity (SOL_K) of the first soil layer was increased which resulted in an increase in baseflow.

Finally, the temporal distribution of the flow and the shape of the hydrograph were improved through calibration of the stormflow lag time (SURLAG) and the baseflow recession constant (ALPHA_BF).

Table 3.2 lists the ranges and the calibrated values of the adjusted parameters used for streamflow calibration for the Arroio Lino watershed. All other parameters were kept at the SWAT default values.

Table 3.2 - The SWAT model parameters included in the final calibration and their initial and final ranges.

Parameter	Description	Range	Initial Value	Calibrated Value
ALPHA_BF	Baseflow alpha factor (days)	0.0 to 1.0	0.048	1
CN2	Initial SCS runoff curve number for moisture condition II	± 25%	30 to 100	+10%
CNCOEF	Curve number coefficient	0.5 to 2.0	0	0.5
ESCO	Soil evaporation compensation factor	0.0 to 1.0	0.95	1
FFCB	Initial soil water storage expressed as a fraction of field capacity water content	0.0 to 1.0	0	1
GW_DELAY	Groundwater delay time (days)	0 to 500	31	5
ICN	Daily curve number calculation method	0 or 1	0	1
PHU	Potential heat unit (used for tobacco)	1000 to 2000	1800	1000
	Potential heat unit (used for corn)	1000 to 2000	1800	1450
	Potential heat unit (used for beans)	1000 to 2000	1800	1350
REVAPMN	Threshold depth of water in the shallow aquifer for revap to occur (mm)	0 to 500	1	300
SOL_AWC	Available water capacity of the soil layer (mm H_2O mm soil^{-1})	± 25%	Default	-5%
SOL_K	Saturated hydraulic conductivity of the soil (mm h^{-1})	± 25%	Default	+5%
SURLAG	Surface runoff lag coefficient (days)	0 to 4	4	1

Monthly observed and simulated streamflow matched well during both calibration (2005) and validation (2004) periods (Figure 3.3) at the watershed outlet. The streamflow statistics for the calibration and validation period are listed in Table 3.3. The monthly calibration and validation r^2 values were 0.90 and 0.86 (> 0.6). Based on Moriasi et al. (2007), model performance was “very good” for the calibration period. This is supported by NSE of 0.87 (> 0.75), the RSR value of 0.35 (≤ 0.50), and PBIAS of -8 % (<±10%). Similarly, for the validation period the model performance was “good” since the NSE was 0.76, the RSR value was 0.49, and PBIAS was -13.3 % (10% < PBIAS < 15%). Since validation assesses the performance of the calibrated model parameter set against a set of independent measured data, it is typically more difficult to get good validation performance in comparison to calibration.

At daily time scale, special attention was given to the magnitude of peak flows and the shape of recession curves. Values in Figures 3.4 and 3.5 represent the daily predicted streamflow compared with the measured data for the calibration and validation periods, respectively. The Table 3.3 also lists the daily calibration and validation calculated statistics. For the calibration period the daily r^2 value was 0.78, whereas for the validation period the r^2 value was 0.59. The daily calibration NSE and RSR were 0.56 and 0.66, respectively, while the validation NSE and RSR were 0.20 and 0.97, respectively.

Table 3.3 - Streamflow statistics for the calibration and validation period.

Statistical Measure		Monthly			Daily		
		Calibration	Validation	Average	Calibration	Validation	Average
Measured (mm)	Mean	94.30	57.25	75.78	3.81	2.31	3.06
	SD	65.62	26.56	46.09	10.50	4.25	7.37
Simulated (mm)	Mean	85.12	49.65	67.38	2.80	1.60	2.20
	SD	66.29	22.96	44.63	8.46	2.97	5.71
r^2	(>0.6)	0.90	0.86	0.88	0.78	0.59	0.69
NSE	(>0.5)	0.87	0.76	0.82	0.56	0.20	0.38
RSR	(≤0.70)	0.35	0.49	0.42	0.66	0.97	0.82
PBIAS	(±25%)	-8.4%	-13.3%	-10.9%	14.6%	30.0%	22.3%

The measured and simulated daily streamflow data were converted to flow duration curves (FDC) (Figure 3.6) to evaluate the daily streamflow variability. The FDC derived from the simulated hydrographs indicated an overestimation of the peak flows and an underestimation of the low flows by the calibrated SWAT model.

Model simulations could not capture the runoff peaks well in daily flow record (Figure 3.6) may be due to uncertainty in the modified Soil Conservation Service curve number method (Mishra and Singh, 2003) used for estimate surface runoff. In the case where the time of concentration of the watershed is less (smaller) than 1 day, the uncertainty in estimated surface runoff from daily rainfall is even higher. Green et al. (2006) argue that as one value represents the range of rainfall intensities that can occur within a day there can be a considerable uncertainty within a day.

For the low flows estimation, a significant variation between the measured and simulated curves can be observed (Figure 3.6). Examination of the complete time series (Figures 3.4 and 3.5) suggests that this error may be partly attributed to the inadequacy of the hydrograph recession simulations. Measured flow presented flatter recessions after the main events than the simulated ones. The consequence of the steeper recession estimation is that the model tended to under-simulate the low flows for this watershed. The deviation between the FDC from simulated and measured low flows may also be partly attributed to limitations in water level sensor measurements and stage-discharge relationship extrapolation procedure used to determine measured low flows.

These inherent uncertainties confirm that the daily peak and hydrograph recession characteristics are critical for model predictions of watershed streamflow. The analysis of FDC also indicated that the runoff peaks, which have a great importance in the sediment and nutrient transport simulation, were better estimated than the low flow.

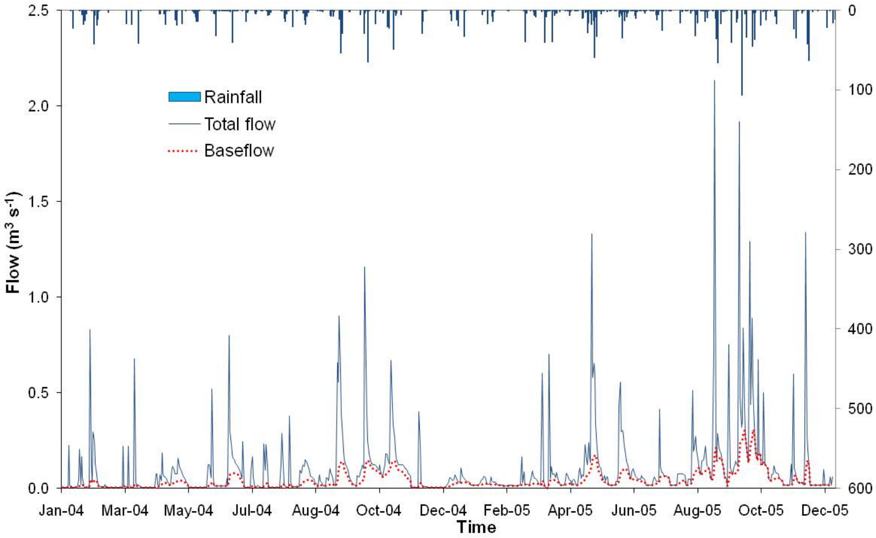

Figure 3.2 – Results of baseflow separation from streamflow hydrograph.

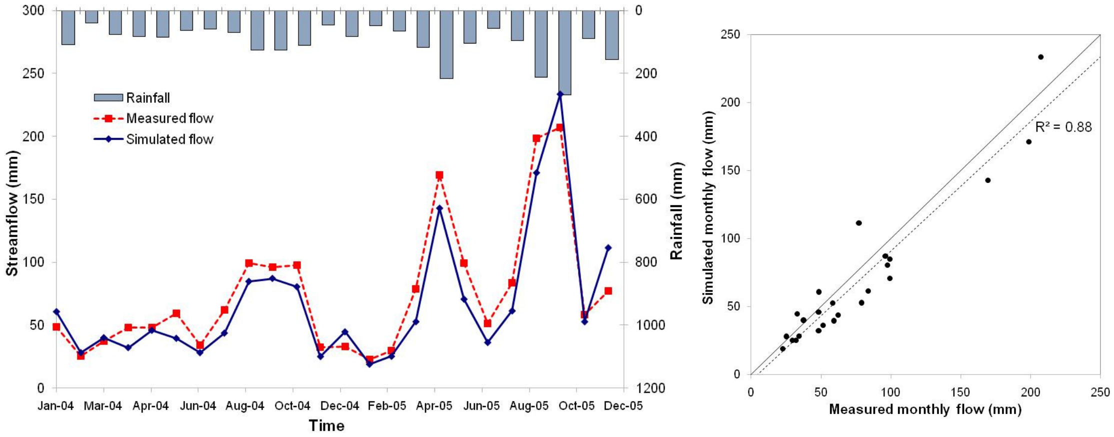

Figure 3.3 – Monthly flow calibration and validation results.

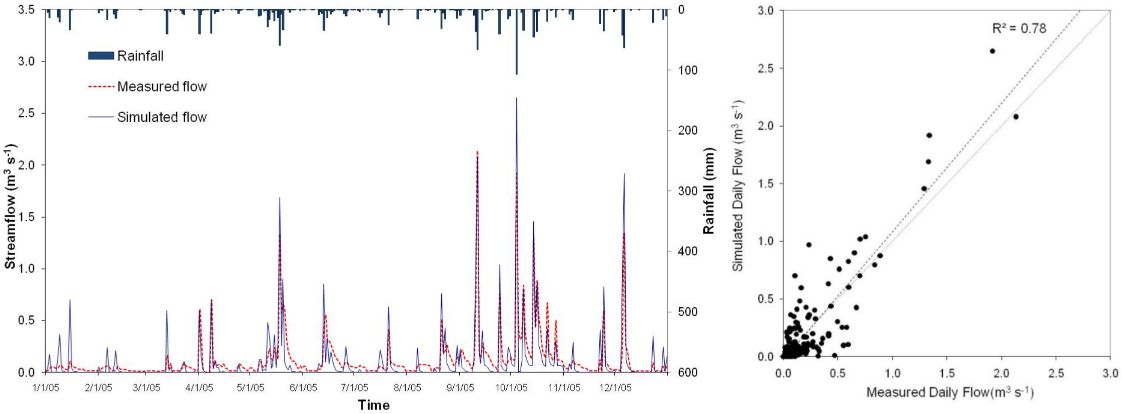

Figure 3.4 – Daily streamflow calibration results.

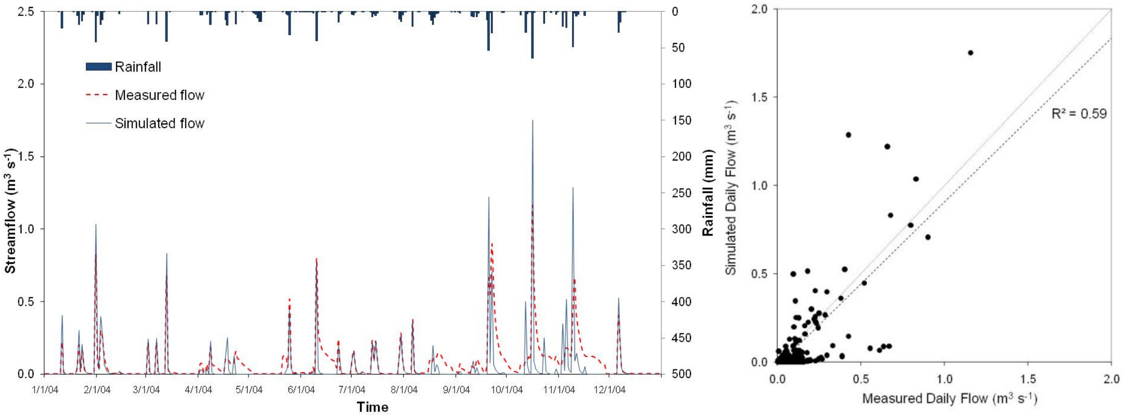

Figure 3.5 – Daily streamflow validation results.

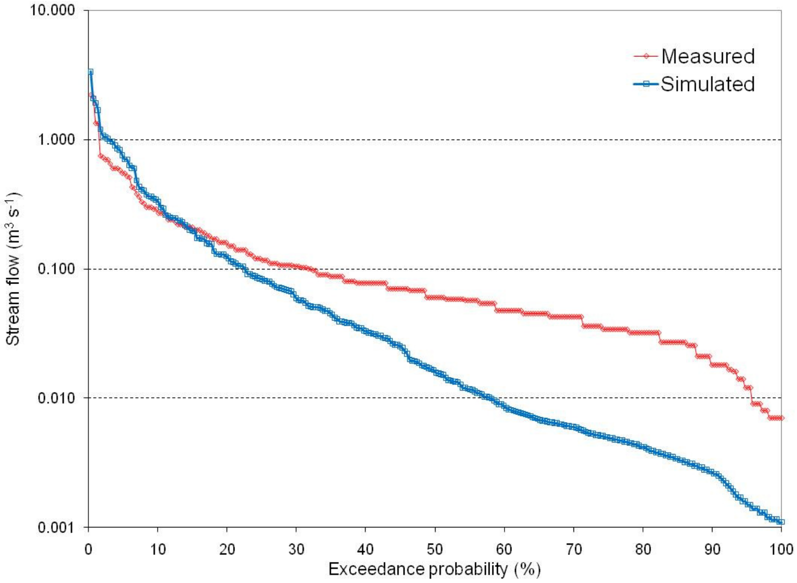

Figure 3.6 – Flow duration curves derived from measured and simulated data from the Arroio Lino watershed for the period 2004-2005.

3.3.3 - Water balance

Average annual values for hydrologic components, such as surface runoff (SURQ), lateral runoff (LATQ), groundwater contribution to streamflow (GW), percolation (PERCO), soil water storage (SW), evapotranspiration (ET) and water yield (WY), were obtained from SWAT outputs (Table 3.4) and compared to calculated values based on precipitation (PREC) and streamflow measurements in Arroio Lino watershed.

Potential evapotranspiration (PET) computed by the SWAT model using the Penman–Monteith equation (Monteith, 1965) was compared with PET data from the INMET weather station (class A pan) (Figure 3.7). Results indicated that PET computed with SWAT follows the same temporal trend as PET data measured, confirming accuracy of the Penman–Monteith approach in the study site (Medeiros, 1998). The PET was corrected for land cover, on the basis of simulated plant growth, to give actual evapotranspiration (ET) (Neitsch et al., 2005). The results indicated that 34 and 41% of the annual precipitation is lost by evapotranspiration in the watershed during calibration and validation periods, respectively. Furthermore, monthly evapotranspiration equals or exceeds monthly precipitation in four months of the year.

Table 3.4 - Predicted water balance components on an annual basis

Period	PREC	SURQ	LATQ	GW	PERCO	SW	ET	PET	WY
2002	2471.4	905.6	557.5	231.8	332.2	95.4	774.4	975.2	1692.0
2003	1482.6	508.4	356.2	121.7	120.9	90.7	491.9	892.6	984.3
2004	990.2	310.9	235.6	51.0	51.9	71.3	409.9	938.0	595.7
2005	1508.9	480.5	422.3	120.9	120.1	94.6	504.4	998.2	1021.4
Average	1613.3	551.3	392.9	131.3	156.3	88.0	545.1	951.0	1073.4

PREC = Precipitation (mm); SURQ = Surface runoff (mm); LATQ = Lateral flow (mm); GW = Groundwater (mm); PERCO = Percolation (mm); SW = Soil water content (mm); ET = Actual evapotranspiration (mm); PET = Potential evapotranspiration (mm); WY = Water yield (mm).

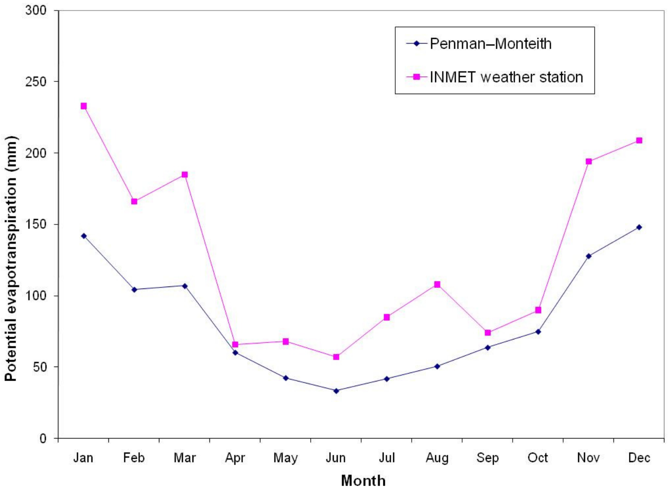

Figure 3.7 – Potential evapotranspiration (PET) computed using the Penman–Monteith equation and measured in the weather station.

Table 3.5 lists the simulated and measured runoff volumes on an annual average basis for the Arroio Lino watershed over the calibration and validation period. The statistical results were better in the calibration period than in the validation period also because the annual rainfall in the calibration period was 34% higher. Overall SWAT seems to simulate wet years better than dry years (Green et al., 2006; Setegn et al., 2010).

Surface runoff contributes 47 and 52% of the water yield during calibration and validation period, respectively, whereas the groundwater contributes 12 and 9% of the water yield during calibration and validation period, respectively.

The annually average simulated surface runoff (396 mm) is 90% of the measured average data value (435 mm). A baseflow index (BFI) (baseflow/total streamflow) was estimated from daily streamflow records using a recursive digital filter method. This approach estimated that the BFI of measured data is 0.51. In comparison, the simulated BFI is 0.52. Therefore, the calibrated model was considered to generate acceptable predictions of baseflow.

Although there is not a well established rainy season for this region, the higher runoff occurred during the months of September and October. Seasonal trends can be depicted by plotting measured and predicted monthly streamflow values against time (Figure 3.3). The largest measured and simulated monthly runoff volume (October 2005) had values of 210.13 mm and 233.52 mm respectively, indicating a difference of only 10%. For the 6 measured events with greater than 40 mm runoff, SWAT overestimated runoff 4 times. This indicates that no clear trend existed for over or underestimation. The error associated with the measured monthly runoff is estimated to average between 5% and 15%.

Table 3.5 - Predicted and measured runoff volumes on an annual basis.

Period	Precipitation (mm)	Water yield (mm)		Surface runoff (mm)		Baseflow (mm)	
		Measured	Simulated	Estimated*	Simulated	Estimated*	Simulated
2004	990.20	685.01	595.74	339.97	310.88	345.04	286.63
2005	1508.90	1109.65	1021.43	528.56	480.51	581.09	543.16
Average	1249.55	897.33	808.59	434.26	395.70	463.07	414.90

* Estimated with the baseflow filter (Arnold and Allen, 1999).

3.4 - Conclusions

Changes in the water balance and environmental contamination are major problems in Southern Brazil due to agricultural activity. The SWAT model was used to simulate the hydrological water balance in the Arroio Lino watershed, located in Southern Brazil.

General agreement between monthly observed and simulated streamflow values was achieved during both calibration and validation periods at Arroio Lino watershed. At daily time scale, time series and flow duration curves for measured and simulated flows were used for testing the quality of the simulations. The results indicated that the model simulations could not capture the runoff peaks well in daily flow record. This is probably due to the uncertainty in the method used for estimating surface runoff from daily rainfall. The model tended to under-simulate the low flows for this watershed which may be partly attributed to the inadequacy of the hydrograph recession simulations and partly attributed to measurements errors. Other factors are the scarcity of input data as well the short period chosen to calibration and validation that could affect the goodness of model fit.

Additionally, it can be concluded that the parts of the curves important for sediment and nutrient transport simulation are better estimated, whereas there is a significant difference in the low flow parts. Despite these limitations, the SWAT model produced accurate simulation results for monthly and annual time steps.

The study has indicated that the SWAT model can produce reliable estimates of the different components of hydrological cycle. Almost 41% of losses in the watershed are through evapotranspiration. The hydrological water balance analysis suggested that baseflow is an important component of the total water yield within the study area that contributes more than the surface runoff.

Having calibrated and validated the SWAT hydrology for the Arroio Lino Watershed, the next step will be to add the sediment and nutrient loading information. This tool will then assist in the simulation of multiple management and land use change scenarios.

3.5 - References

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4 - ARTICLE II: INTEGRATION OF A LANDSCAPE SEDIMENT TRANSPORT CAPACITY INTO SOIL AND WATER ASSESSMENT TOOL MODEL

Abstract

Problem statement: Sediment delivery from hillslopes to the rivers is spatially variable; this may cause long-term delays between initial erosion and the related sediment yield at the watershed outlet. ***Approach:*** In an attempt to account for sediment transport and deposition processes across the landscape, the Soil and Water Assessment Tool (SWAT) model, version 2009, was modified to simulate landscape sediment transport capacity. The model versions were tested on the Arroio Lino watershed, located in Southern Brazil. The observed sediment yield at the watershed outlet was used for model calibration and validation. Model evaluations were conducted by using time series graphs and standard statistical measures. ***Results:*** The new deposition routine performed better during calibration than SWAT model version 2009 (NSE of 0.70 and -0.14, respectively) in the Brazilian watershed, but was not as accurate during validation (NSE of -1.37 and -12.13, respectively). The modified model provided reasonable simulations of sediment transport across the landscape positions. Simulation results indicated that approximately 60% of the mobilized soil is being deposited before it reaches the river channels. ***Conclusion/Recommendations:*** The application demonstrates the applicability of the model to simulate sediment yield in watersheds with steep slopes. These results suggest that integration of the sediment deposition routine in SWAT increases model predictions accuracy in steeper areas, while at the same time significantly improves the ability to predict spatial distribution of sediment deposition areas. Further work is still needed to more broadly test the model in areas with differing topography configuration and land uses.

Keywords: SWAT model; soil erosion, sediment delivery modeling

4.1 - Introduction

Effective control of sediment delivery to rivers is a critical component of watershed management when the aim is to improve water and soil quality. Excessive sediment inputs to rivers due to increased erosion may result in water quality degradation, and high sedimentation rates within the surface water system.

One of the most poorly understood components of the basin sediment system is the relationship between on-site erosion on upland areas (i.e. the field) and sediment yields as measured at the drainage basin outlet (i.e. the river) (Slattery, 2002). It is well known that only a fraction, and perhaps a small fraction, of the eroded sediment within a drainage basin will find its way to the basin outlet and be represented in the sediment yield (Walling, 1983). Although the sediment yield is directly related to the intensity of surface erosion, the sediment transport and storage within a watershed is highly variable through space. Even in small watersheds this may cause long-term delays between erosion in upland areas and the related sediment yield at outlet gage.

An “upland area” in a watershed is where surface runoff can be considered as overland flow in hydrological analysis. Upland erosion is affected by hydrology, topography, soil erodibility and transportability, vegetation cover, land use, subsurface effects, tillage roughness and tillage marks (Foster, 1982).

Analyzing the processes controlling sediment yield at all scales within a watershed, Lane et al. (1997) verified the trend from soil detachment to sediment transport and deposition to sediment transport capacity dominating as watershed scale increases. Sediment transport capacity of overland flow is the maximum flux of sediment that flow is capable to transport (Aksoy and Kavvas, 2005).

The concept of sediment transport capacity is often used in modeling sediment movement via overland flow and in channel transport models (Merritt et al., 2003). Many physically based soil erosion models included the concept of sediment transport capacity of overland flow, such as that proposed by Meyer and Wischmeier (1969), ANSWER model (Beasley et al., 1980; Park et al., 1982), WEPP model

(Nearing et al., 1989), LISEM model (de Roo et al., 1996), and EUROSEM model (Morgan et al., 1998).

In contrast, some empirical studies used the concept of a sediment delivery ratio (SDR) in order to represent the sediment lag between sediment yield and erosion.

The greatest need is for the development of approaches in the middle of this spectrum which can combine the operational simplicity of the delivery ratio concept with the physically-based perspective of the mathematical models which because of their data and computational requirements remain essentially a research tool (Walling 1983).

In order to avoid the need for a lumped SDR, some methods have been developed to predict sediment delivery and deposition including the calculation of sediment transport capacity (Van Rompaey et al., 2001).

The Soil and Water Assessment Tool (SWAT; Arnold et al., 1998) is a watershed scale model that contains both conceptual and physical based approaches. The SWAT model has been applied to watersheds throughout the world (Arnold and Fohrer, 2005; Gassman et al., 2007) to determining the impact of land management practices on water, sediment and agricultural chemical yields (Neitsch et al., 2005). This model uses Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) for calculating soil erosion and sediment yield in each Hydrologic Response Unit (HRU). The original SWAT model already models landscape process using slope classes while dividing the HRU's, however; it does not account the deposition process across the landscape.

First approaches to the sediment transport capacity have used the shear stress (Yalin, 1972), stream power (Bagnold, 1966), or unit stream power (Yang, 1972). Prosser and Rustomji (2000) made a review of the sediment transport capacity relations for overland flow and concluded that there is concordance between the empirical studies and theoretical considerations of boundary shear stress, mean stream power and unit stream power.

Using dimensional analysis, Julien and Simons (1985) demonstrated that when rainfall intensity is spatially uniform, sediment transport capacity per unit width of slope, denoted q_s, can be represented by the following relationship:

$$q_s = k_1 q^{\beta} S^{\gamma} \qquad (1)$$

where q is the discharge per unit width; S is the local energy gradient; and k_1, β and γ are derived either empirically or theoretically. Variables such as gravitational acceleration, water density, sediment cohesion, density and particle size are all represented by k_1.

The discharge is most practically estimated using some relationship between upslope contributing area and discharge. Rustomji and Prosser (2001) used a modified form of the relationship proposed by Kirkby (1988):

$$q = k_2 a^{\lambda} \tag{2}$$

where a is hillslope area per unit width of contour (m^2/m) and λ and k_2 are empirically derived constants.

Equation 2 was incorporated into equation 1 by Rustomji and Prosser (2001) to produce a purely topographic rule for predicting the sediment transport capacity of overland flow across a landscape (assuming parameters k_1 and k_2 are held spatially constant):

$$q_s = k_1 k_2 (a^{\lambda})^{\beta} S^{\gamma} \tag{3}$$

The value of λ can be varied to represent several modes of hillslope hydrology behaviour. For steady-state flow condition, $\lambda = 1$.

Based on a review of transport capacity experimental studies, Prosser and Rustomji (2000) found that selecting the median value of 1.4 for the constants β and γ is appropriate for use in sediment transport modeling. Therefore, equation 3 can be rewritten as:

$$q_s = k_1 k_2 a^{1.4} S^{1.4} \tag{4}$$

On the other hand, Desmet and Govers (1995) calculated sediment transport as a proportion of the local erosion potential (E_p):

$$E_p = k_1 A^m S^n \text{ and } TC = ktc_2 E_p \tag{5}$$

where TC equals the transport capacity of overland flow and Ktc_2 is a proportionality factor.

This concept was used by Van Rompaey et al. (2001) to calculate the transport capacity in the SEdiment DElivery Model (SEDEM):

$$TC = ktc.R.K.(LS - 4.1.s^{0.8}) \tag{6}$$

where TC is transport capacity (kg m^{-2} $year^{-1}$), *ktc* is the transport capacity coefficient, *R* is the rainfall erosivity factor (MJ mm m^{-2} h^{-1} $year^{-1}$), *K* is the soil erodibility factor (kg h MJ^{-1} mm^{-1}), *LS* is the slope and slope length factor, and *s* the slope gradient (m m^{-1}).

The product of the constants k_1 and k_2 in equation 4 reflects landscape characteristics that influence sediment transport, such as rainfall intensity, soil erodibility and vegetation, and landscape characteristics that influence runoff generation. Verstraeten et al. (2007) replace these constants with the *R* and *K* factor as these equations represent rainfall and soil characteristics. The authors compare the use of this approach to calculate transport capacity and the use of transport capacity as calculated with equation 6 in SEDEM model and concluded that the new approach provides better results in the prediction of erosion and sediment deposition.

In order to account for sediment movement across the watersheds slopes the SWAT routines were carefully examined and some improvements in the sediment routines were proposed. Thus, the major objective of this study is twofold: (i) to integrate a landscape sediment transport capacity into SWAT model and (ii) to test their workability using field data at a small agricultural watershed in Southern Brazil.

4.2 - Materials and Methods

4.2.1 - SWAT sediment routine

SWAT model is distributed with FORTRAN source code. The model can be set up using the ArcSWAT interface, an upgrade of AVSWAT-X (Di Luzio et al., 2004), a software system that links ArcGIS software and the model. In addition to ArcSWAT, another interface for the model has been developed using an open source GIS system, MapWindow SWAT (MWSWAT) (George and Leon, 2007).

Using the GIS interface the watershed is partitioned into a number of sub-watersheds based on a digital elevation model (DEM) and is further sub-divided into hydrological response units (HRU) with unique soil/landuse/slope characteristics. Flow, sediment, nutrient, and pesticide loadings from each HRU in a sub-watershed are summed, and the resulting loads are routed through channels to the watershed outlet.

The erosion caused by rainfall and runoff is computed with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). The MUSLE equation has an implicit delivery ratio built into it that is a function of the peak runoff rate, which in turn is a function of the drainage area:

$$sed = 11{,}8.(Q_{\sup}.q_p.area_{hru})^{0{,}56}K.C.P.LS.CRFG \qquad (7)$$

where *sed* is the sediment yield on a given day (metric tons), Q_{surf} is the surface runoff volume (mm ha^{-1}), q_{peak} is the peak runoff rate (m^3 s^{-1}), $area_{hru}$ is the area of the HRU (ha), *K* is the USLE soil erodibility factor (metric ton m^2 hr (m^3-metric ton cm)$^{-1}$), *C* is the USLE cover and management factor, *P* is the USLE support practice factor, *LS* is the USLE topographic factor, and *CFRG* is the coarse fragment factor.

The slope length and the slope steepness parameters used in the calculation of the MUSLE topographic factor (LS-factor) are sensitive factors that can greatly affect the SWAT sediment yield predictions. The ArcSWAT interface calculates the slope length and the slope steepness from the DEM. However, the calculation of slope length does not always succeed when slopes are steep. When a slope length is not calculated, the interface defaults to a slope length of 50 m. The default slope length of 50 m is appropriate for relatively flat watersheds, but in watersheds with steep average slopes (> 25 percent), SWAT will simulate excessive sheet erosion (EPA, 2004).

The USLE length-slope factor is a measure of the sediment transport capacity of runoff from the landscape, but fails to fully account for the hydrological processes that affect runoff and erosion (Moore and Burch, 1986).

The topographic factors have a physical basis (Moore and Burch, 1986), so that they do, in a gross sense, work correctly in planar and convex hillslopes. However, their ability to take account of the effect of transport capacity on sediment delivery does not extend to situations where the transport capacity decreases in the downslope direction (Kinnell, 2008).

After the sediment yield is evaluated using the MUSLE equation, the SWAT model further corrects this value considering sediment lag in surface runoff. The SWAT model also calculates the contribution of sediment to channel flow from lateral and groundwater sources (Chaubey et al., 2007).

The channel sediment routing equation uses a modification of Bagnold's sediment transport equation (Bagnold, 1977) that estimates the transport concentration capacity as a function of velocity. The model either deposits excess sediment or re-entrains sediment through channel erosion depending on the sediment load entering the channel.

The sediment yield modeled by SWAT is done so for each unique HRU in the watershed, independent of position within each subbasin. There is currently no option to include upslope contributing area while defining HRU's (White, 2009).

In an attempt to simulate a landscape unit routing of sediment SWAT model version 2009 was modified. A sediment transport capacity of overland flow (Rustomji and Prosser, 2001; Verstraeten et al., 2007) was calculated using a landscape delineation routine (Volk et al., 2007). The landscape sediment transport capacity was included in the SWAT code to limit the sediment delivery from the HRU's to the reaches.

4.2.2 - Landscape unit delineation

A landscape delineation routine (Volk et al., 2007) based on the slope position method (USDA Forest Service, 1999) was used to delineate landscape units from a DEM.

The slope position of a cell is its relative position between the valley floor and the ridge top. Filling sinks and leveling peaks is the first step of the method and important to make the valleys and ridges fairly continuous. Downhill and "uphill" flow accumulation values greater than user specified limits are used to identify valleys and ridges, respectively. When large limits are used only large valleys and ridges will be identified as such, and small valleys and ridges will be considered somewhere mid-slope. Slope position is calculated for the cells in the output grid as the elevation of each cell relative to the elevation of the valley the cell flows down to and the ridge it flows up to. This is presented as a ratio, ranging from 0 (valley floor) to 100 (ridge top). Hillslope areas are represented by the values between these two ranges (Volk et al., 2007).

The figure 4.1 illustrates a representative hillslope with landscape units within each sub-watershed.

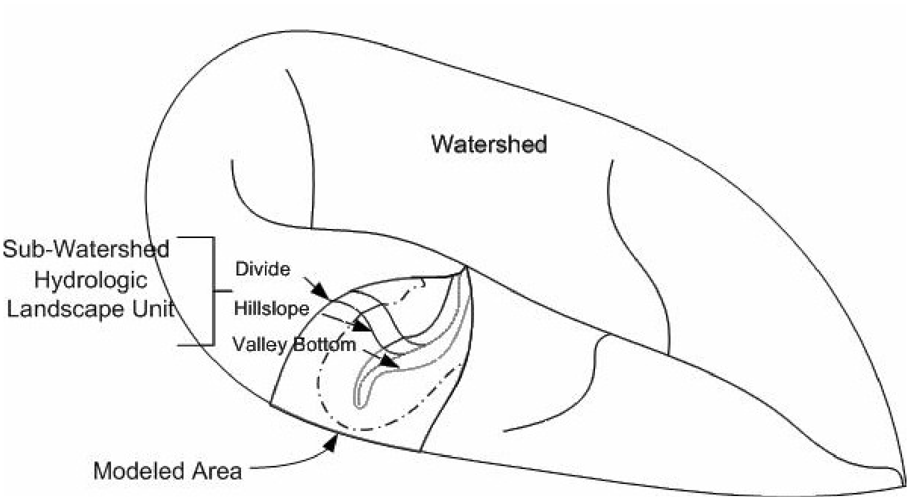

Figure 4.1 – Sub-watershed landscape delineation within a watershed (Volk et al., 2007).

4.2.3 - Sediment delivery to valley floors

In order to include a sediment deposition routine a landscape transport capacity of overland flow was calculated and incorporated to the SWAT code. The landscape transport capacity (TC) was calculated using the following equation (Verstraeten et al., 2007):

$$TC = ktc * R * K * a^{1.4} S^{1.4} \qquad (8)$$

whereby *ktc* reflects the vegetation component within the transport capacity.

The transport capacity parameter, *ktc*, represents the slope length needed to produce an amount of sediment equal to a bare surface with an identical slope gradient (Verstraeten, 2006). The *ktc* parameter is dependent on the land cover, Verstraeten et al. (2007) calibrated *ktc* for three different land use categories: well vegetated surfaces (natural forest, *ktc* = 0.04), moderately well vegetated surfaces (improved and overgrazed pasture, *ktc* = 0.6) and poorly vegetated surfaces (cropland, *ktc* = 4).

The figure 4.2 schematically illustrates the representation of the hillslope – valley network used for calculate the landscape transport capacity parameters, such as the hillslope area per unit width of contour (q) and the slope (S). The valley side zone is the valley floor calculated with the landscape delineation routine (Volk et al., 2007).

The hillslope area per unit width of contour (a) is referred to as unit hillslope area, and is a measure of mean hillslope length (Rustomji and Prosser, 2001):

$$a = \frac{total\_hillslope\_area}{(2xvalley\_length)} \tag{9}$$

For each hillslope-valley floor element, the hillslope area (m^2) and the length of valley floor (m) were calculated.

Slope (S) is calculated as the mean gradient of the valley side cells in the DEM:

$$S = \frac{\sum_{i=1}^{n} d8slope_i}{n} \tag{10}$$

The eroded sediment was routed to the river channel network taking into account the transport capacity of each spatial unit. If the amount of routed sediment exceeds the local transport capacity, sediment deposition occurs.

If the sum of the sediment input and the local sediment production is lower than the transport capacity then all the sediment is routed further downslope. If this sum exceeds the transport capacity then sediment output is limited to the transport capacity. In the latter case, limited erosion will occur if the transport capacity exceeds the sediment input. If the transport capacity is lower than the sediment input, there will be sediment deposition (Van Rompaey *el al.*, 2001).

The sediment yield (SY in t yr^{-1}) can be expressed as an absolute value. An area-specific value (SSY in t ha^{-1} yr^{-1}) can be calculated when the absolute sediment yield value is divided by the size of the drainage basin.

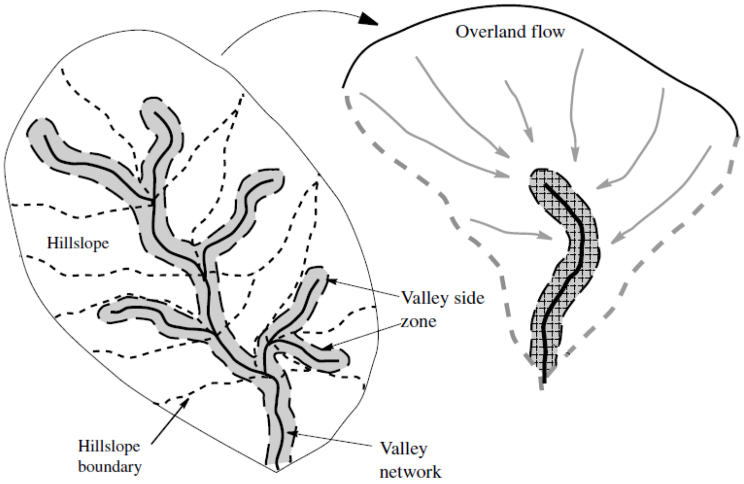

Figure 4.2 - Schematic illustration of the hillslope – valley network used in the model. (Adapted from Rustomji and Prosser, 2001).

4.2.4 - Case study: the Arroio Lino Watershed

The new SWAT sediment routine was tested on the Arroio Lino watershed, located in Agudo county, State of Rio Grande do Sul, Brazil. The small watershed (4.8 km^2) is included in a heavily cultivated region in Southern Brazil.

The watershed topography ranges from undulated to heavily undulated relief (Kaiser et al., 2010). *Chernossolos* (Mollisols) predominate, but *Neossolos* (Entisols) are found on steeper slopes (Dalmolin et al., 2004; USDA, 1999).

Almost 30% of the Arroio Lino watershed area is occupied by annual crops and more than 50% by native forest cover. Approximately 90% of the crops areas are devoted to tobacco production (Pellegrini et al., 2009).

Due to the steep terrain, geological structure, and rock units, the drainage patterns have headwaters on steep slopes. Agriculture increased surface runoff and hillslope erosion due to the removal of native vegetative cover in Arroio Lino watershed. These affects have contributed to excessive sediment loads inputs to the streams.

Estimated soil erosion rates from cropland was 0.28 cm ha^{-1} year (Sequinatto, 2007), which are greater than both soil formation and soil loss tolerance rates. According to Sequinatto (2007) these data indicate the unsustainable use of the soils for tobacco growth under current management practices.

4.2.5 - Input data

The landscape transport capacity parameters for the Arroio Lino watershed were derived from the same input data for SWAT model, such as topography, soil properties, land use and climate data.

Land use was determined by field surveys, assisted by a GPS with a GIS software (Pellegrini et al., 2009). The land use map provides a spatial coverage of the transport capacity parameter (*ktc)*. The land use categories were grouped into five major categories: water, urban land use, crops, forest and pasture. Initial *ktc* values were applied to every land use category (based on the values adopted by Verstraeten et al., 2007): 0 for waters and urban land use, 0.04 for forest, 0.6 for pasture and 4 for crops. (desconsiderando o manejo).

The mean annual rain erositivity (R) was assumed to be constant throughout the watershed at 6400 MJ mm ha^{-1} h^{-1} $year^{-1}$ based on rainfall data for the meteorological station.

The soil erodibility (K) was estimated from the soil map and soil physical and chemical properties. The soil map identifies 11 soil types, the main soil types are Entisols and Mollisols (USDA, 1999). The K values range from 0.12 to 0.15 t h $MJ^{-1}mm^{-1}$; with a mean value of 0.14 t h $MJ^{-1}mm^{-1}$.

Topographic data were obtained in the form of Digital Elevation Model (DEM) at 10 m resolution. The watershed was divided into 21 sub-watersehds using the automated delineation tool of the GIS interface based on the DEM for the watershed. The slope map was divided in five slope classes: 0-5%, 5-15%, 15-30%, 30-45%, and >45%. A realistic combination of land use, soil type and slope classes resulted in 344 hydrologic response units (HRU's). The landscape delineation routine based on the DEM (Volk et al., 2007) resulted in a landscape units map (Figure 4.3) with three main landscape units: divide, hillslope and floodplain.

For the quantification of the sediment yield, data for channel flow and suspended sediment concentration were obtained at the watershed outlet. Water samples were manually collected after each 1-cm water level variation using a US DH 48 suspended sediment sampler during rain events. Sediment yields were calculated with a sediment rating curve that was developed using the flow and suspended sediment measurements (Sequinatto, 2007). The sediment yield data at the watershed outlet were used for model sensitivity analysis, calibration and validation.

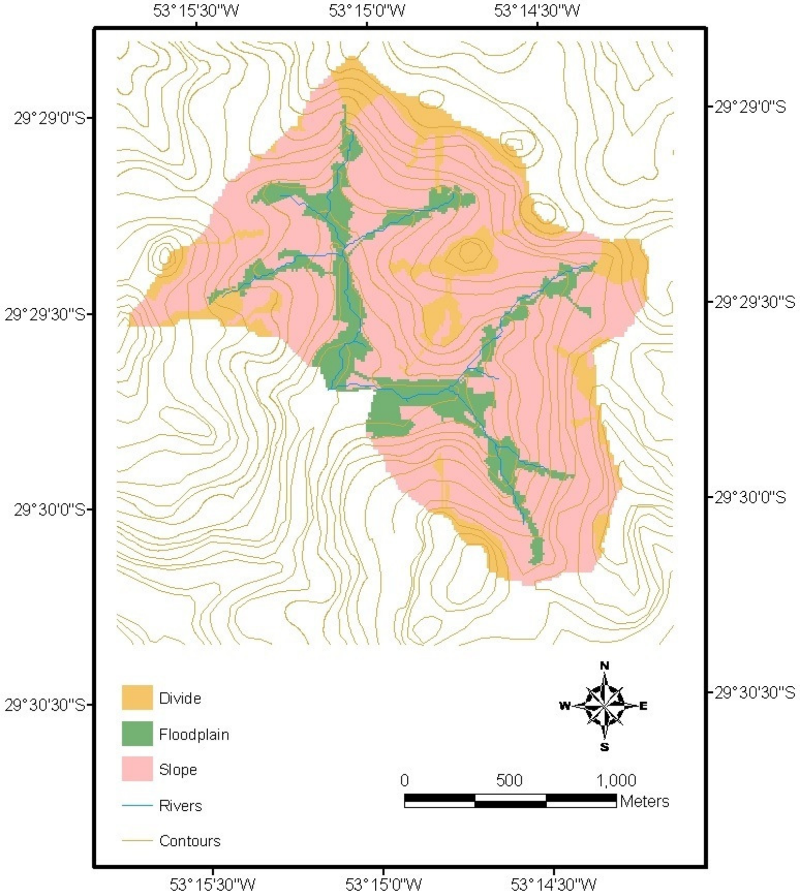

Figure 4.3 - Landscape units map of Arroio Lino watershed.

4.2.6 - Model evaluation

SWAT performance was evaluated using graphical comparison and statistical analyses to determine the quality and reliability of the predictions when compared to observed values. Summary statistics include the mean and standard deviation (SD), where the SD is used to assess data variability. The goodness-of-fit measures were the coefficient of determination (r^2), the Nash-Sutcliffe efficiency (NSE) value (Nash and Sutcliffe, 1970), the percent bias (PBIAS) and the ratio of the root mean square error to the standard deviation of measured data (RSR) (Moriasi et al., 2007).

In order to assess how well the model performed, Green et al. (2006), Green and van Griensven (2008) and Wu and Chen (2009) used standards of NSE > 0.4 and $r^2 > 0.5$. Santhi et al. (2001) assumed a monthly NSE > 0.5 and a monthly $r^2 > 0.6$ and obtained an acceptable model performance. According to Moriasi et al., (2007) model simulation can be judged as satisfactory if NSE > 0.50 and RSR ≤ 0.70, and if PBIAS ± 55% for sediments for monthly time step. For this study, $r^2 > 0.6$, NSE > 0.50, RSR ≤ 0.70, and PBIAS ± 55% were chosen as standards for acceptable simulations.

- Calibration

As suggested by Neitsch et al. (2005), streamflow (Chapter 3 - Article I) was calibrated first and sediment yield was calibrated afterward based on a combination of manual and auto-calibration (Green and van Griensven, 2008). Predicted sediment yield for monthly and daily calibration was calculated from the SED_OUT model output for the appropriate subbasin in the main channel output file from SWAT.

To determine if the new SWAT sediment routine was indeed a more accurate version of SWAT2009, both versions used the same input data and were subject to the same calibration process. Additionally, model statistics from the new SWAT sediment routine were compared to the SWAT2009 version.

4.3 - Results and Discussion

4.3.1 - Initial simulations

Simulation was carried out from January 1, 2001 to December 31, 2005. The period from January 1, 2001 to December 31, 2003 serves as a warm-up period for the model. The warm-up period was used to establish appropriate initial conditions for soil water storage. The outlet gauge data from January to December 2005 were used to optimize the calibration parameters and the remaining data for validation.

Initially the simulations were made with SWAT2009 standard version. As the sediment yield was overpredicted, the relative error was +190%, the simulated sediment yield was decreased through calibration of the following parameters: USLE support practice factor (USLE_P), Initial SCS runoff curve number for moisture condition II (CN2), Average slope steepness (Slope) and Average slope length (Slsubbsn).

However, even after calibration the sediment yield simulated was very high, the relative error was +84%, compared with the observed values.

Similarly, Uzeika (2009) did not find satisfactory results for sediment yield simulation at a steep small watershed (1.19 km^2) in Southern Brazil, with SWAT model. The author says that this may be related to limitations in the equation that simulates sediment load (MUSLE) or to the sediment propagation in the channel. She also related the overprediction of sediment yield with sediment deposition, since large volumes of sediment were deposited in depressions in the fields near the alluvial channel in that watershed, indicating that not all the soil eroded on the hillslopes reach the stream.

The possible reason why SWAT model overpredict sediment yield in steep slope watersheds is that SWAT is not able to capture the undulations in the landscape; i.e. after a 45% slope the landform is depressed and the sediment deposits there. However, SWAT keeps the sediment in flow resulting in an overestimation of sediment load at the stream outlet.

4.3.2 - Implementing sediment landscape routine

SWAT code was modified in an attempt to simulate a landscape unit routing of sediment. Simulation was carried with this new version of the model using the same input data as used to simulate with SWAT standard version.

Table 4.1 gives the predicted sediment yield from hillslopes to river channels in the Arroio Lino watershed. The sediment supply (contribution) from the HRU's (SY_MUSLE) is calculated by the MUSLE equation (Equation 7). The landscape transport capacity (TC) is calculated by equation 8. The predicted sediment yield from hillslopes to river channels (SY) is limited by the TC value. Approximately 60% of the mobilized soil is being deposited (DEP) before it reaches the river channels. Hence, sediment delivery from hillslopes to river channels is rather limited with an average value of 19.70 t ha^{-1} year^{-1}. The predicted total soil loss equals 15217 t, but only 6054 t of sediment is being delivery from the hillslopes to the channel network in the Arroio Lino watershed.

Table 4.1 - Prediction of hillslope sediment delivery for the Arroio Lino Watershed.

Subbasin	TC		SY_MUSLE		SY		DEP	
	(t ha^{-1})	(t)	(t ha^{-1})	(t)	(t ha^{-1})	(t)	(t ha^{-1})	(t)
1	2.45	44.51	37.02	673.21	2.45	44.51	34.57	628.69
2	23.87	585.65	53.34	1308.56	23.87	585.65	29.47	722.89
3	0.58	1.98	13.28	45.35	0.58	1.98	12.71	43.37
4	40.00	1670.80	70.57	2947.75	40.00	1670.80	30.57	1276.95
5	0.00	0.00	1.08	0.14	0.00	0.00	1.08	0.14
6	60.32	1561.36	46.43	1201.89	46.43	1201.88	0.00	0.00
7	18.81	620.48	43.31	1428.52	18.81	620.48	24.50	808.02
8	91.08	642.39	49.00	345.60	49.00	345.60	0.00	0.00
9	3.97	82.76	36.18	753.32	3.97	82.76	32.21	670.58
10	11.53	138.70	50.14	603.33	11.53	138.70	38.61	464.63
11	3.17	33.14	56.90	593.98	3.17	33.14	53.73	560.84
12	32.59	293.73	59.96	540.50	32.59	293.73	27.38	246.77
13	-	-	1.01	0.04	1.01	0.04	0.00	0.00
14	1.44	17.30	43.72	524.89	1.44	17.30	42.28	507.59
15	0.95	2.08	29.81	65.61	0.95	2.08	28.87	63.53
16	1.10	9.30	30.27	257.04	1.10	9.30	29.17	247.74
17	1.97	16.87	76.47	654.81	1.97	16.87	74.50	637.94
18	2.38	14.92	45.19	283.03	2.38	14.92	42.81	268.11
19	3.07	55.85	54.69	993.64	3.07	55.85	51.62	937.82
20	31.05	490.21	45.17	712.95	31.05	490.21	14.11	222.75
21	14.52	428.36	43.49	1282.82	14.52	428.36	28.97	854.47
Total	21.84	6710.40	49.52	15217.00	19.70	6054.17	28.33	9162.83

TC = landscape transport capacity, SY_MUSLE = sediment supply from the HRU's calculated by the MUSLE equation, SY = sediment yield from hillslopes to river channels, DEP = Deposition.

4.3.3 - Model versions comparison

Upon calibration of sedimentologic parameters using the auto-calibration procedure, SWAT sediment deposition routine returned more accurate results than the standard SWAT for the Arroio Lino watershed. Figures 4.4 and 4.5 illustrate the scatter plots of monthly measured and simulated sediment yields for both the calibration and validation periods at the watershed outlet. The model versions statistics are listed in table 4.2. A monthly NSE value of 0.70 (NSE $\leq$ 0.75) for the calibration period was achieved, with an r^2 of 0.77. SWAT sediment deposition routine accuracy decreased for the validation period, with NSE and r^2 values of -1.37 and 0.61, respectively.

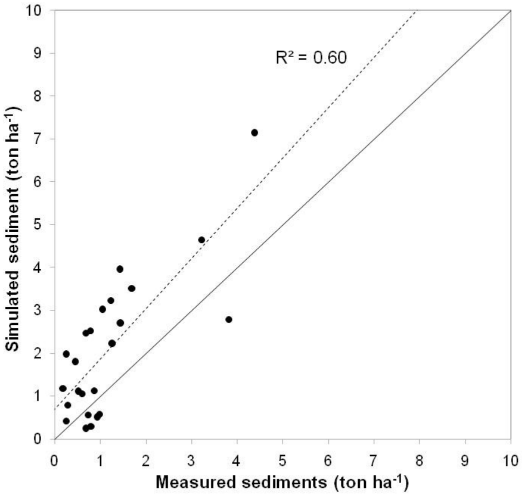

Figure 4.4 - SWAT modeled sediment yield versus measured sediment yield for Arroio Lino watershed.

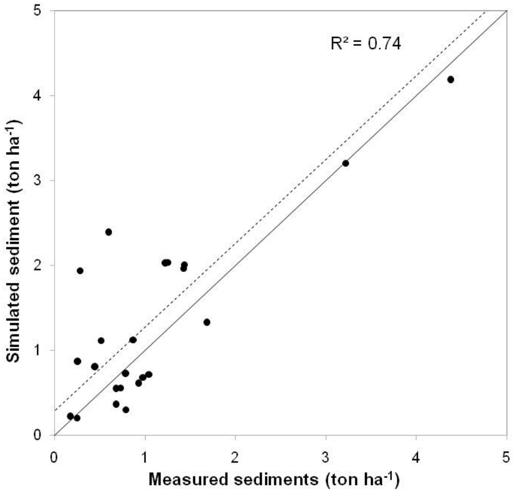

Figure 4.5 - SWAT deposition routine modeled sediment yield versus measured sediment yield for Arroio Lino watershed.

Table 4.2 - Overall model statistics for sediment yield in Arroio Lino watershed.

Statistical Measure		SWAT			SWAT modified		
		Calibration	Validation	Average	Calibration	Validation	Average
Measured (mm)	Mean	1.43	0.94	1.18	1.43	0.94	1.18
	SD	1.51	0.33	0.92	1.51	0.33	0.92
Simulated (mm)	Mean	2.63	1.53	2.08	1.77	1.15	1.46
	SD	1.88	1.25	1.56	1.63	0.68	1.15
r^2	(>0.6)	0.70	0.50	0.60	0.77	0.61	0.69
NSE	(>0.5)	-0.14	-12.13	-6.14	0.70	-1.37	-0.33
RSR	(≤0.70)	1.07	3.62	2.35	0.57	1.54	1.06
PBIAS	(±55%)	84%	63%	73%	14%	22%	18%

SWAT deposition routine distributes sediment delivery much differently than the standard SWAT2009 standard version. SWAT2009 predicts that all HRU's within the watershed would delivery sediment in the same proportion regardless of their position in the landscape. Conversely, with SWAT deposition routine some HRU's would delivery sediment, while others would storage sediment. Both model versions predicted higher sediment loads delivery for some upland areas (Figures 4.6 and 4.7), but the SWAT deposition routine predicted much less sediment being delivery in the low-lying, flatter areas near the river channel network.

In a previous research, Minella et al. (2007) evaluated the sediment sources at Arroio Lino watershed and concluded that the major sediment source were the crop fields (68.3%). However, sediment delivery from the source areas (crops) to the drainage is highly variable through space within Arroio Lino watershed.

In other research in Arroio Lino watershed, Sequinatto (2007) analyzed a large rainfall event and concluded that the right side drainage of the watershed contributed with 80% of the sediment yield and presented higher values of LS factor, more intense soil erosion, presence of highways and gullies and smaller riparian zone.

SWAT2009 standard version predicted that the right side drainage of the watershed contributed with 53% of the sediment yield while the SWAT deposition routine predicted that the right side drainage of the watershed contributed with 69%. These results indicate that the new sediment routine tends to outperforms the SWAT2009 standard version in simulate the spatial distribution of sediment delivery from hillslopes to river channels.

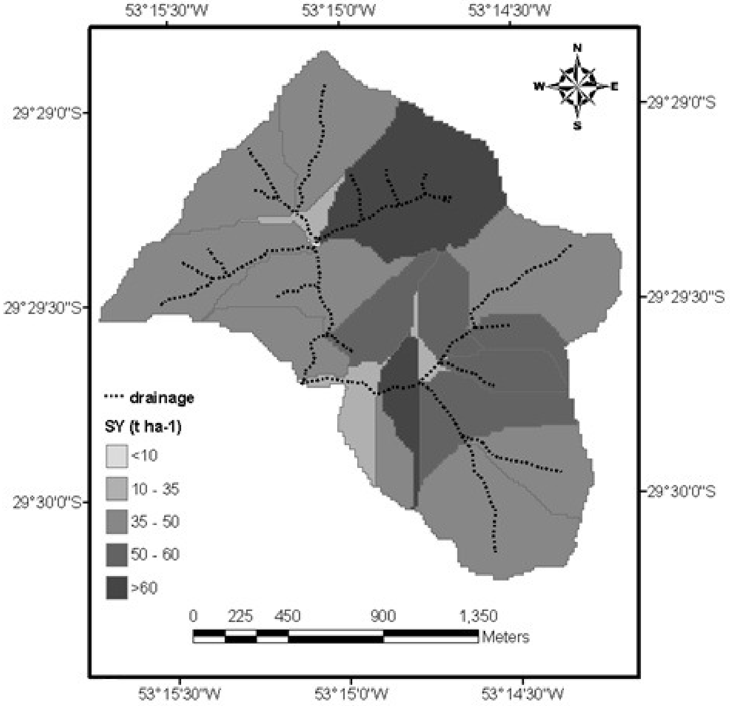

Figure 4.6 - Spatial distribution of sediment delivery in Arroio Lino watershed modeled by standard SWAT2009 model.

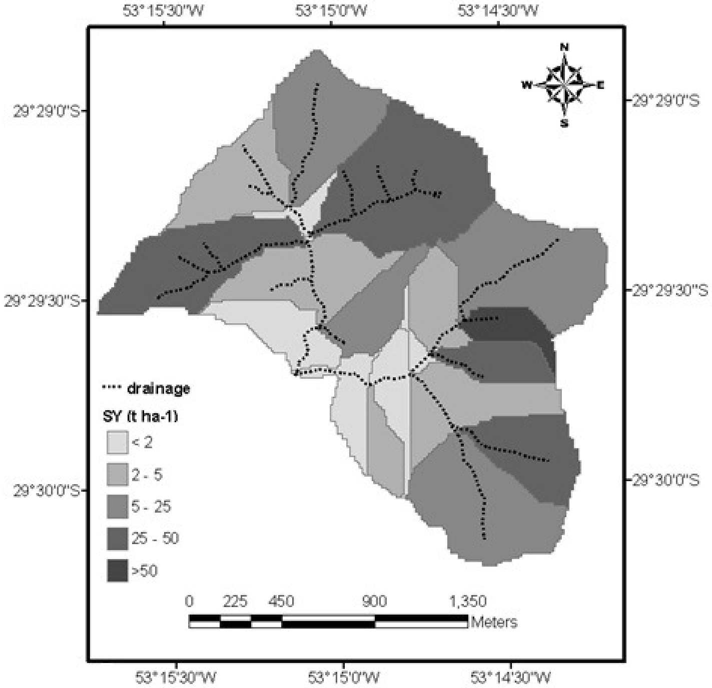

Figure 4.7 - Spatial distribution of sediment delivery in Arroio Lino watershed modeled by SWAT deposition routine.

4.4 - Conclusions

The concept of sediment transport capacity of overland flow is often applied to the modeling of watershed erosion. The SWAT model version 2009 already models landscape processes using slope classes while dividing the HRU's, but it does not account for the deposition process across the landscape. In this study, an attempt was made to include the sediment transport capacity description in the source code of the SWAT model version 2009.

The SWAT model version 2009 and the new SWAT sediment routine were tested on the Arroio Lino watershed, located in Southern Brazil. The new SWAT sediment routine was more accurate in modeling sediment yield at the watershed outlet than SWAT2009 version. Additionally, intrawatershed sediment delivery areas were modeled with higher spatial resolution than SWAT2009 due to the inclusion of the landscape transport capacity as introduced in the sediment deposition routine. Simulation results indicated that approximately 60% of the mobilized soil is being deposited before it reaches the river channels.

Despite the promissing results of the new SWAT sediment routine simulation, the calibration of the transport capacity parameters (*ktc*) in the new sediment routine has yet to be adequately solved, so further research is needed to address the uncertainties involved. This new sediment routine needs to be applied and evaluated using others input datasets, especially in areas where reliable spatial sediment transport patterns and spatially distributed depositional data is available.

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5 - ARTICLE III: SIMULATION OF PHOSPHORUS LOSSES FROM AN INTENSIVE AGRICULTURE WATERSHED

Abstract

Problem statement: Phosphorus transfer from agricultural soils to surface waters is an important environmental issue. Application of large amounts of mineral fertilizers in intensive agricultural regions in Southern Brazil contributes to excessive phosphorus loads in soils and water bodies. ***Approach:*** The Soil and Water Assessment Tool (SWAT) model is designed to assess nonpoint and point sources of pollution. The model was tested on the Arroio Lino watershed, located in Southern Brazil. Observed phosphorus loads at the watershed outlet and at four sub-watersheds (A1, A2, B, C) were used for model parameter sensitivity analysis and calibration. Model evaluations were conducted by using time series graphs and statistical measures. ***Results:*** The model was most sensitive to the P soil partitioning coefficient (PHOSKD), P percolation coefficient (PPERCO), Nitrogen soil partitioning coefficient (NPERCO) and deep aquifer percolation fraction (RCHRG_DP). The predicted P loads are in the order of magnitude of the measured ones, however, the statistics analysis indicated more accurate results for watershed outlet than for sub-watersheds simulations. ***Conclusion/Recommendations:*** Although cropland occupies only 29% of the total land cover it is the primary source of nutrients in the watershed (80%). Based on the results obtained in this study, SWAT is assessed to be a feasible model for phosphorus transfers simulation and have the potential to provide a strong base for water quality management in Brazilians watersheds.

Keywords: SWAT model; Nutrients, Phosphorus loads

5.1 - Introduction

Phosphorus (P) in the soil can be originated from natural or anthropogenic processes such as the fertilization of agricultural environments. Under conditions of appropriate management, P is absorbed by plants and used for the processes of growth and reproduction. However, under conditions of deficient management, P is removed from the soil by runoff and erosion processes, being carried away to the water courses and eventually causing serious environmental damages, such as the eutrophication of the water bodies.

Areas under tobacco crops, in Southern Brazil, are intensively cultivated and receive application of large amounts of mineral fertilizers. Although the P fertilization is a necessary practice to assure adequate tobacco production, excessive nutrient input can result in the impairment of water quality. The crop production system, integrated to the tobacco industry, does not use any technical agronomic–environmental criteria for fertilizing recommendations. The fertilizing doses employed are the same for all the farmers of Southern region of Brazil, independent of soil type, clay content, or historical fertilizer use (Pellegrini et al., 2009).

The assessment of potential water quality impacts of nutrient related diffuse source pollution, especially agriculture activities, are necessary to achieve the sustainable development of natural resources such as land and water.

The recognition of P as major contributor to water quality has led to the development of a number of water quality models with the objective of predicting the transport of P from soils to waters (Miller et al., 2009).

The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998) is a semi-distributed model developed to predict the impact of the diffuse and the point sources of pollution on water quality in watersheds with varying soils, land use and management conditions (Neitsch et al., 2005). Applications of SWAT model for modeling P loading from agricultural land uses have been expanded worldwide, such as Abbaspour et al. (2007), Green et al. (2007) and Lin et al. (2007). Nasr et al. (2007) tested three mathematical models, namely SWAT, Hydrological Simulation Program–FORTRAN (HSPF) and Systeme Hydrologique Europeen TRANsport

(SHETRAN)/Grid Oriented Phosphorus Component (GOPC) of diffuse P pollution, to explore their suitability in Irish conditions for future use. The authors concluded that SWAT gave the best simulation results for daily total phosphorus loads. Radcliffe et al. (2009) suggested methods to estimate P-related SWAT parameters in soils and calibrate in-stream processes with SWAT. Neves et al. (2006) applied the SWAT model to a Brazilian watershed, aiming to evaluate the nitrogen (N) and phosphorus (P) entry into springs. Baltokoski et al. (2010) evaluated the sensitivity of SWAT model to simulate the flow rate and total P load in other two Brazilian watersheds.

This study evaluates the ability of SWAT (Arnold et al., 1998; Arnold and Fohrer, 2005) to simulate P losses in the Arroio Lino watershed in Southern Brazil. Thus, the objectives of this study were to: (1) conduct parameter sensitivity analysis, (2) calibrate the SWAT model for P loads in the four sub-watersheds and in the watershed outlet, and (3) evaluate spatial variability of P losses throughout the watershed.

5.2 - Materials and Methods

5.2.1 - Study area description

The study area is the Arroio Lino watershed, located in Agudo County, in the state of Rio Grande do Sul, Brazil. The small agricultural watershed (4.8 km^2) is impacted primarily by crop land use and high fertilization rates.

Concerning geological aspects, the watershed belongs to the "*Serra Geral* Formation," which presents basaltic hillsides and localized outcrops of *Botucatu* sandstone. The altitudes range from 100 to 500 m with steep topography and slopes greater than 25° (Pellegrini et al., 2009). *Chernossolos* (Mollisols) predominate, but *Neossolos* (Entisols) are found on steeper slopes (Dalmolin et al., 2004; USDA, 1999). The vegetation is composed by remnants of seasonally deciduous forests in different stages of succession (Pellegrini et al., 2009).

Climate in the region is humid subtropical (Cfa type), according to the Köppen classification, with an average temperature of more than 22 °C in the hottest, and between -3°C and 18 °C in the coldest month. Rains are usually well distributed, ranging from 1,300 to 1,800 mm year^{-1} (Kaiser et al., 2010).

Almost 30% of the Lino stream watershed area is occupied by annual crops and more than 50% by native forest cover. Approximately 90% of the cropping areas are devoted to tobacco production, most of the tobacco crop is cultivated under conventional tillage with intense agricultural exploration. The tobacco crops requires high agricultural inputs, especially chemical fertilizer containing N, P, K, and S (Pellegrini et al., 2009). These aspects have contributed to high levels of P in the water streams (Gonçalves et al., 2005).

5.2.2 - SWAT Model

SWAT is a widely used watershed-scale transport model that includes algorithms for modeling different forms of soil P (Neitsch et al., 2005). SWAT simulates a watershed by dividing it into multiple subbasins, which are further divided into hydrologic response units (HRU's). These HRU's are the product of overlaying soils, land use and slope classes. The yield or total nutrient for a subbasin is the sum of all the HRU's it contains.

The model simulates P transfers in three parts. The first part deals with the transformations and movement of P within a HRU based on soil P cycle. SWAT monitors six different pools of P in the soil: active, stable and fresh organic P; and active, stable and soluble inorganic P (Neitsh et al., 2005). According to Chaubey et al. (2007), the solution P is actually labile P in conformance with the original Erosion Productivity Impact Calculator (EPIC) version of the P module as described in Jones et al. (1984) and Sharpley et al. (1984). Labile P was defined by Sharpley et al. (1984) as the P that can be extracted from soil using an anion exchange resin and therefore represents solution P plus weakly sorbed P.

The second part focuses on the transport processes of P via surface runoff (soluble forms) and erosion (P attached to sediment). Additionally, baseflow P concentrations can be set to simulate lateral subsurface flow and ground water contributions to the river loads.

Third part is the river channel phase and it includes water, sediment, and P routing along river reaches. P transformations are described with an adapted version of the QUAL-2E in-stream water quality model (Radcliff et al., 2009).

5.2.3 - Input data

The parameters in SWAT that are responsible for P generation, transport, and transformation processes include P management parameters (such as fertilization rate), soil properties, P concentrations in soils, erosion and sediment delivery and transport related parameters, as well as parameters governing rainfall-runoff processes in upland areas and channels (Lin et al., 2007).

Topographic data were obtained from contour lines in the form of Digital Elevation Model (DEM) at 10 m resolution. Using the automated delineation tool GIS interface, the watershed was partitioned into 21 sub-basins and reaches. The slope map was divided in five slope classes: 0-5%, 5-15%, 15-30%, 30-45%, and > 45%. A realistic combination of land use, soil type and slope classes resulted in 344 hydrologic response units (HRU's).

Land use was determined by field surveys, assisted by a Global Positioning System (GPS) with a GIS software (Pellegrini et al., 2009). Principal land uses in the watershed consist of cultivated tobacco fields, forest, pasture and fallow. A detailed list of agricultural management operations carried out in the watershed with dates; type of operation and application rates was created. The list included planting of crop, fertilizer application, tillage, and harvest. In SWAT, the SCS curve number parameter (CN2) is updated for each management operation. The date of operation may vary from year to year depending on the cumulative days exceeding the minimum (base) temperature for plant growth. The potential heat units for the annual plants were calculated and the values were added in the management input file (.mgt). Nutrient fractions for fertilizers used in the watershed were included in SWAT fertilizer database file (fert.dat). Soil fertilization for tobacco was based on the recommendation of tobacco industries, that is 850 kg ha^{-1} of NPK fertilizer 10-18-24 at planting and 400 kg ha^{-1} of sodium nitrate (14-0-14) in topdressing (Kaiser et al., 2010).

Soil parameters are used in computations for infiltration, runoff, groundwater flow, and P transport. The digital soil map (1:15,000) includes 11 soil types, mainly Entisols and Mollisols (Dalmolin et al., 2004; USDA, 1999). The key soil physical and chemical properties were analyzed for each soil and the soils information was added in the SWAT user soils databases.

Initial amounts of labile P concentration (SOL_SOLP) and organic P concentration (SOL_ORGP) in the surface soil layer can be either specified by the model user or designated with SWAT model default values. For this study, soil samples were collected from the 0–0.10 m layer at 20 points chosen in order to represent the spatial variability of soil uses, including areas with annual crops, natural pastures, native forests, and reforestation. The samples were transported and analysed at the Soil Chemistry and Fertility Laboratory of the Federal University of Santa Maria. The labile P concentration (SOL_SOLP) was estimated by extraction with an AER membrane (Rheinheimer et al., 2003) and organic P concentration (SOL_ORGP) was extracted by ignition. The SWAT default values for labile P are 5 mg P kg^{-1} soil for unmanaged land under native vegetation and 25 mg P kg^{-1} soil for cropland conditions (Neitsch et al., 2005; Chaubey et al., 2007), which compare to the labile P measured values, would not be appropriate.

The P sorption coefficient (PSP, or P availability index PAI) and P soil partitioning coefficient (PHOSKD) were based on a previous research made on the watershed (Pellegrini et al., 2009). SWAT takes a single value of PSP and PHOSKD for the entire watershed, so area-weighted average concentrations were used.

For the other parameters like P_UPDIS and PPERCO model default values were used as little or no information about their values were available in the study area.

Rainfall data were obtained from an automatic meteorological station and from five rain gauges installed within the watershed (Kaiser et al., 2010; Sequinatto, 2007). Rainfall data for the watershed have been collected from 2001 to 2005. Daily maximum and minimum temperature, solar radiation, wind speed and humidity values were also obtained from the automatic meteorological station. The gaps in the climate data were completed with information from the Brazilian National Institute of Meteorology (INMET) and National Water Agency (ANA) stations adjacent to the watershed.

Streamflow and sediments measured at the watershed outlet (Gonçalves et al., 2005; Sequinatto, 2007) and water quality data measured at five monitoring points (A1, A2, B, C and outlet) within the watershed (Gonçalves et al., 2005; Sequinatto, 2007; Gonçalves, 2007; Pellegrini et al., 2009) were used for model evaluation. The monitoring points were chosen once they characterize sub-watersheds with different land use positions in the landscape (Figure 5.1) (Pellegrini et al., 2009):

- Sub-watershed A, with a landscape conformation characterized by steep slopes and high human activities. Agricultural fields are closed to streams and no protection by vegetation in stream-adjacent areas. The annual crops represent 12% of drainage area of sample point A1 (upstream) and almost 25% of drainage area of sample point A2 (downstream);
- Sub-watershed B, with a landscape conformation characterized by steep slopes and low human activities; the downstream point present few agricultural fields (16% of the sub-watershed area);
- Sub-watershed C, with a landscape conformation characterized by steep slopes and high human activities. Almost 25% of the sub-watershed area is under annual crops; however, the agricultural fields are far from streams since the natural vegetation are around stream areas.

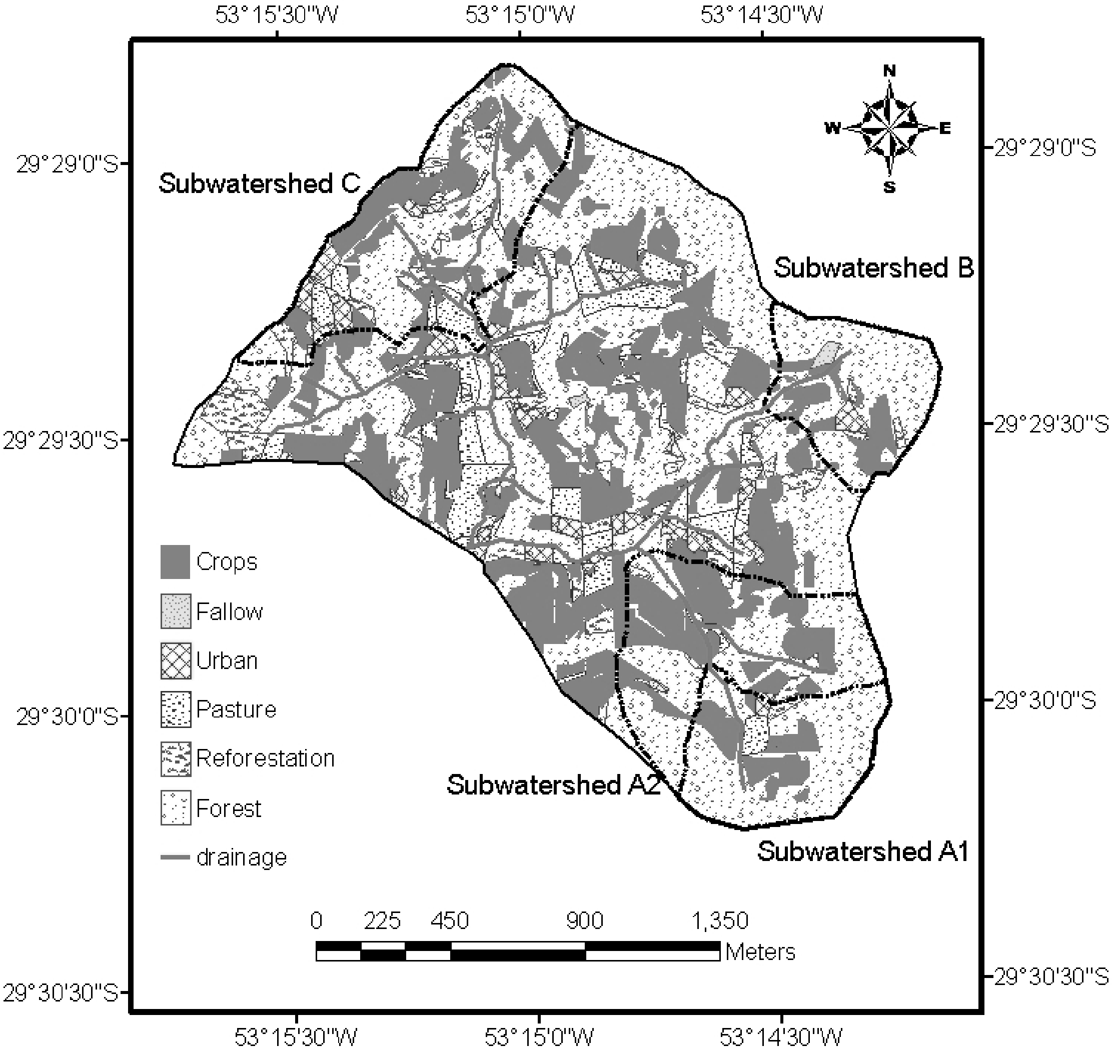

Figure 5.1 – Sub-watersheds of Arroio Lino watershed.

5.2.4 - Parameter Sensitivity Analysis and Calibration

In order to analyze the effect of model parameters on the model output directly and on model performance a parameter sensitivity analysis tool embedded in SWAT was used (van Griensven et al., 2002).

As suggested by Neitsch et al. (2005), streamflow (Chapter 3 - Article I) and sediments (Chapter 4 – Article II) at the watershed outlet were calibrated first based on a combination of manual and auto-calibration procedure (Green and van Griensven, 2008) and the P concentrations in streams were calibrated afterward.

The uncalibrated SWAT run showed clear faults in the ability to describe observed processes. In this study, the trial-and-error method was adopted for model calibration and the parameter values were varied one-at-a-time to cover all possible combinations of the parameters. Parameter values were adjusted from the initial estimates given in the model within the acceptable ranges listed in Table 5.1 to achieve the desired proportion. Model calibration was accomplished by changing the values of the model parameters that were found to have a significant effect on the output of the model. The model then ran the possible combinations of parameters and calculated model performance. This procedure was repeated until optimal parameter values were found.

Besides the P data at the watershed outlet, P loads from four tributaries to Arroio Lino based on previous studies (Gonçalves et al., 2005; Pellegrini et al., 2009) were also used as part of the calibration procedure.

5.2.5 - Model evaluation

SWAT performance was evaluated using graphical comparison and statistical analyses to determine the quality and reliability of the predictions when compared to observed values. Summary statistics include the mean and standard deviation (SD), where the SD is used to assess data variability. The goodness-of-fit measures were the coefficient of determination (r^2), the Nash-Sutcliffe efficiency (NSE) value (Nash and Sutcliffe, 1970), the percent bias (PBIAS) and the ratio of the root mean square error to the standard deviation of measured data (RSR) (Moriasi et al., 2007).

In order to assess how well the model performed, Green et al. (2006), Green and van Griensven (2008) and Wu and Chen (2009) used standards of NSE > 0.4 and $r^2 > 0.5$. Santhi et al. (2001) assumed a monthly NSE > 0.5 and $r^2 > 0.6$ indicated acceptable model performance. According to Moriasi et al. (2007) model simulation can be judged as satisfactory if monthly NSE > 0.50, RSR ≤ 0.70, and if PBIAS ± 70% for nutrients. Nevertheless, when watershed models are applied on a single-event basis or in a daily time step the evaluation guidelines can be less strict than for longer time steps (Moriasi et al., 2007).

5.3 - Results and Discussion

5.3.1 - Phosphorus Parameters Sensitivity Analysis and Calibration

Sensitivity analysis was carried out using nine parameters of SWAT model suggested as being the most sensitive for the P simulation (van Griensven et al., 2006). Among these parameters, the model was most sensitive to the P soil partitioning coefficient (PHOSKD), P percolation coefficient (PPERCO), Nitrogen soil partitioning coefficient (NPERCO), and deep aquifer percolation fraction (RCHRG_DP).

Simulation using default values underestimated P loads. Model calibration was required to correct these simulation errors. The simulated P loads were increased through calibration of the following parameters: PHOSKD, PPERCO, NPERCO and P enrichment ratio for sediment loading (ERORGP), phosphorus availability index (PSP .bsn), P enrichment ratio with sediment loading

Table 5.1 lists the ranges and the calibrated values of the adjusted parameters used for P calibration for the Arroio Lino watershed. All other parameters were kept at the SWAT default values.

Table 5.1 - SWAT model parameters included in the calibration and their initial and final ranges.

Parameter	Description	Range	Initial Value	Calibrated Value
NPERCO	Nitrogen soil partitioning coefficient (m^3 mg^{-1})	0 to 1	0.2	1
PHOSKD	Phosphorus soil partitioning coefficient (m^3 mg^{-1})	100 to 200	175	175
PPERCO	Phosphorus percolation coefficient (10 m^3 mg^{-1})	10 to 17.5	10	17.5
PSP	Phosphorus availability index	0.01 to 0.7	0.4	0.5-0.7
Rchrg_Dp	Deep aquifer percolation fraction	0 to 1	0.01	0
ERORGP	Phosphorus enrichment ratio for sediment loading	0.5 to 5.0	0.5	5

5.3.2 - Spatial pattern of P source areas

In order to evaluate the spatial distribution of P transfers, P measured loads were compared with SWAT simulation results in five monitoring points in the Arroio Lino watershed. Figure 5.3 illustrates the daily average P losses for the four sub-watersheds (A1, A2, B and C) and the watershed outlet for 2002-2005. The solid line is the 1:1 line, and the dashed line is the linear regression line. Most of the regression lines are close to the 1:1 line, indicating that the averaged measured data closely matches the simulated data, the r^2 value is below 0.6 only in the sub-watershed A1.

In addition to the scatter plots (Figure 5.3), box and whisker plots for the measured and simulated P are provided in Figure 5.2. Box and whisker plots based on the median, 25th percentile, and 75th percentile of the daily averages from SWAT ($A1_s$, $A2_s$, B_s, C_s, $OUTLET_s$) were compared to the box plots of the median, 25th percentile, and 75th percentile of the measured samples ($A1_o$, $A2_o$, B_o, C_o, $OUTLET_o$). Each box itself represents the middle 50% of the data (bounded by the lower quartile, median, and upper quartile), and the minimum and maximum values represented by the lower and upper whisker, respectively. The analyses of the box and whisker plots indicate that SWAT simulated total P were within the range of observed values at different sites. SWAT underestimated total P in downstream points of sub-watersheds A (A2), B, C and in the watershed outlet, but the model overestimated total P in the upstream point of sub-watershed A (A1).

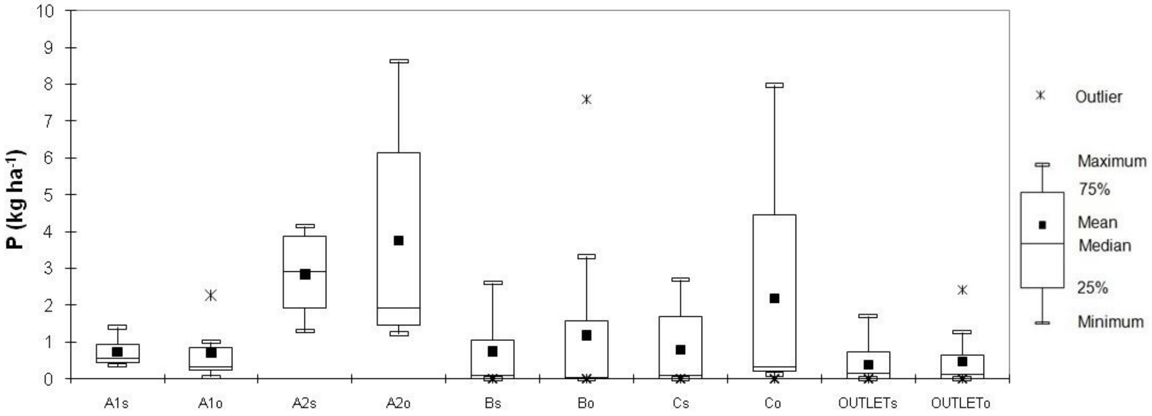

Figure 5.2 – Box and whisker plots of observed and simulated values of total P at five monitoring points of Arroio Lino watershed.

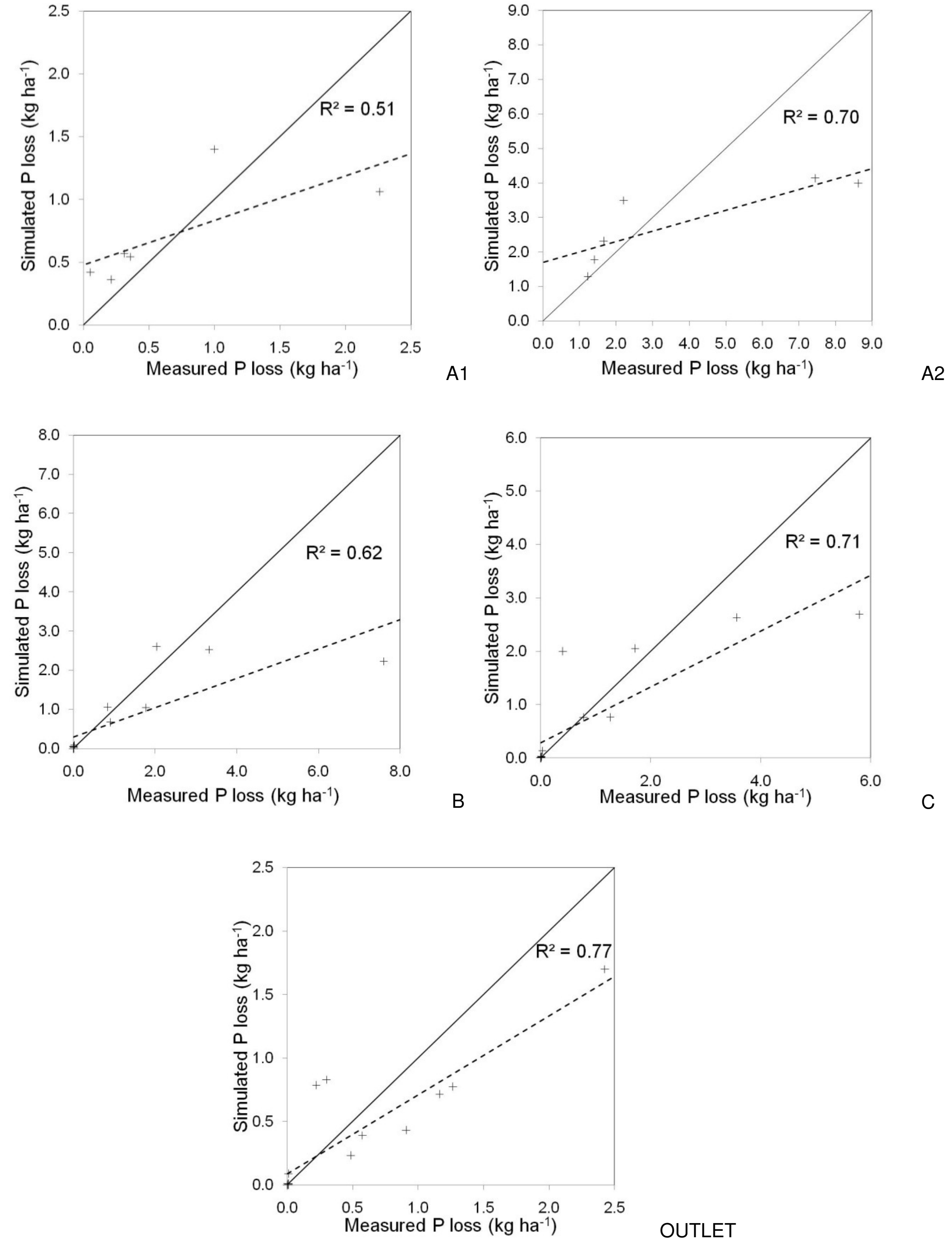

Figure 5.3 – Measured and simulated P losses for the five monitoring points of Arroio Lino watershed.

Table 5.2 summarizes the statistical data for the measured total P and SWAT simulation total P results. The sub-watersheds with the highest mean P load simulated were the ones with the highest mean P load measured (A2 > C > B > A1). The SWAT model often underestimated total P in the Arroio Lino watershed, only in the sub-watershed A1 the model overestimated the total P (-4%). The model performance was more accurate for watershed outlet than for the sub-watersheds. This is supported by NSE of 0.73, the RSR value of 0.52 and PBIAS of 19 %. Similarly, for the sub-watershed C model performance was quite as good since the NSE was 0.65, the RSR value was 0.59, and PBIAS was 22 %. The NSE values are below 0.5 and the RSR values are slightly above 0.7 in the sub-watersheds A1, A2 and B. Harmel et al. (2006) suggested that the uncertainty of measured data must be considered to appropriately evaluate watershed models. Thus, it was very difficult to correctly evaluate the model performance as the P sampling was not systematically performed in storm events.

Table 5.2 - Summary statistics of measured and simulated parameters of P losses constituent per sub-watershed in Arroio Lino watershed.

Statistical Measure		Sub-watershed				Outlet
		A1	A2	B	C	
Measured (kg ha^{-1})	Mean	0.70	3.76	1.18	2.26	0.92
	SD	0.83	3.35	2.54	2.06	0.72
Simulated (kg ha^{-1})	Mean	0.73	2.83	0.74	1.82	0.73
	SD	0.41	1.20	0.75	0.85	0.48
R^2	(1)*	0.51	0.70	0.62	0.71	0.77
NSE	(1)*	0.46	0.38	0.48	0.65	0.73
RSR	(0)*	0.73	0.79	0.72	0.59	0.52
PBIAS	(0)*	-4%	25%	37%	22%	19%

* Perfect fit values.

Although the predicted P loads are in the order of magnitude of the measured ones, the model was not so accurate when predicting the P loads in the sub-watersheds A1, A2 and B. One possible reason is that calibration of streamflow and sediment parameters were made only in the watershed outlet, which difficulted the calibration of P related parameters in the sub-watersheds. According to Abbaspour et al. (2007) a watershed model calibrated based on measured data at the outlet of the watershed may produce erroneous results for various land uses and subbasins within the watershed. This means that a large amount of measured data is necessary for a proper model calibration.

Another reason could be the SWAT algorithms used for estimate P desorption/adsorption. SWAT utilizes a linear isotherm for desorption/adsorption based on the simplified model (EPIC) developed by Jones et al. (1984) and Sharpley et al. (1984). According to Vadas et al. (2006) this simplified model underestimated soil P desorption and the authors suggested replacing EPIC's constant sorption and desorption rate factor with more dynamic rate factors. In a study of the P dynamics conducted in Arroio Lino watershed, Pellegrini et al. (2008) successfully adjusted the desorption of soils to the non-linear Langmuir isotherm (Barrow, 1983). In another study, Gonçalves (2007) characterize the mineralogy of eroded sediments of Arroio Lino watershed and concluded that the 2:1 clays predominate in the 2 µm fraction of sediment and also detected the low concentration of clay and iron (Fe) oxides, which play a great role in P immobilization for their high reactivity. Consequently the sediment has low adsorption of phosphate, which facilitate its desorption to the water bodies (Gonçalves, 2007). SWAT under estimated the high P loads at Arroio Lino watershed possibly because its desorption/adsorption model were not able to simulated this low soil capacity to retain P. Since soils differ in clay mineralogy, Fe, Al, and Ca contents, and pH, and these all affect sorption/precipitation, they differ substantially in their capacity to retain P. The use of non-linear isotherms and sorption parameters that consider soil properties, such as clay mineralogy and Fe content, could improve the SWAT P predictions.

SWAT predicted a total phosphorus load of 10,500 kg P/year. The distribution of P loading by each land cover category is given in Figure 5.4. A large portion of the Arroio Lino watershed was forest land (~60%), followed by tobacco crop (~25%), pastures (~9%), others crops (4%), and roads (~3%). Although cropland (tobacco and others crops) occupies only 29% of the total land cover, it contributed with almost 80% of the soluble P transported by surface runoff, 76% of the mineral P sorbed to sediment and 67% of the organic P transported with sediment into the reach. One explanation is the high initial labile P levels in cropland soils. In addition, the application of fertilizer increases phosphorus loss since the surface application increases the availability of phosphorus for surface runoff and sediment transport.

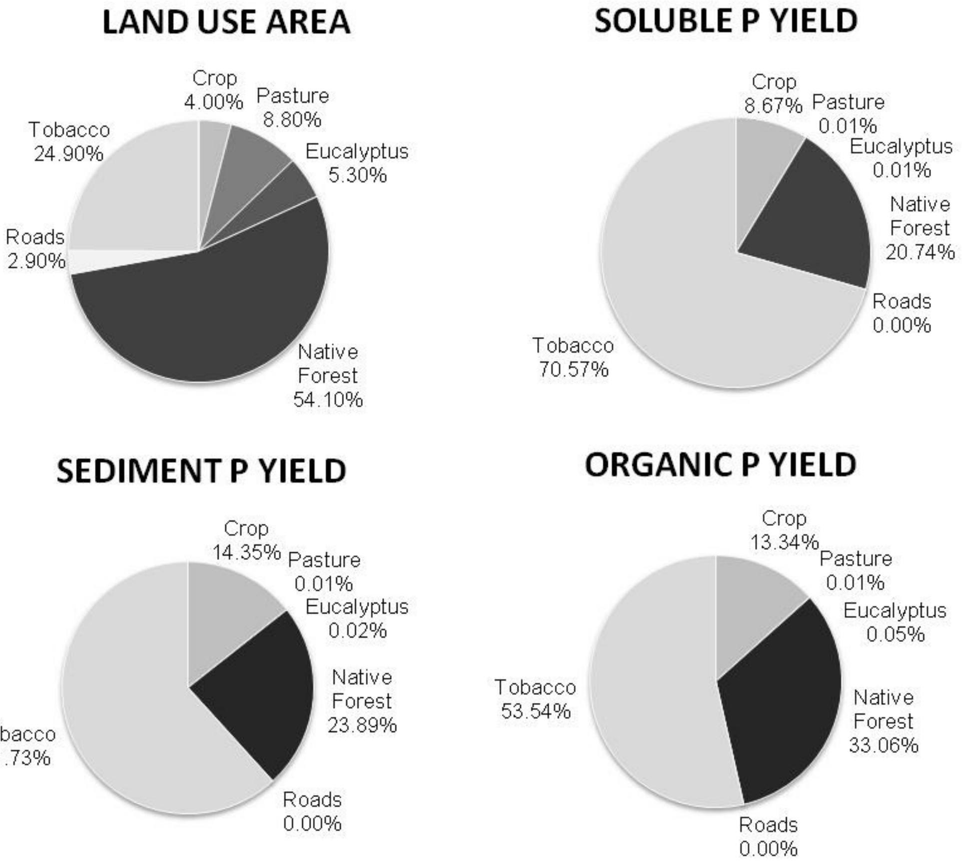

Figure 5.4 – P load distribution among various land use categories based on SWAT model simulation.

5.4 - Conclusions

The SWAT model was tested in the Arroio Lino watershed, a small agricultural watershed located in Southern Brazil. The model was able to predict the range of phosphorus concentrations in surface waters. However, the model often underestimated total phosphorus in the watershed, the relative error at the outlet was 19% for total phosphorus.

Croplands (tobacco and others crops) were the primary source of nutrients in Arroio Lino watershed. Although cropland occupies only 29% of the total land cover, it contributed with almost 80% of the soluble P transported by surface runoff, 76% of the mineral P sorbed to sediment and 67% of the organic P transported with sediment into the reach. One explanation is the high initial labile P levels in cropland soils. In addition, the application of fertilizer increases phosphorus loss since the surface application increases the availability of phosphorus for surface runoff and sediment transport.

Five monitoring points of water quality variables were selected in order to assess the ability of SWAT model in simulating P transfers in sub-watersheds with different land use positions in the landscape within the Arroio Lino watershed. It was very difficult to evaluate the model performance as the P sampling was not systematically performed in storm events. Nonetheless, the predicted P loads are in the order of magnitude of the measured ones. The statistics analysis also indicated that more accurate results can be obtained in the monitoring points where a previous calibration of streamflow and sediment parameters was made. The lack of sufficient phosphorus data for validation was a challenge in this study and should be addressed further in future studies.

Based on the results obtained in this study, SWAT is assessed to be a feasible tool for water quality management in Brazilians watersheds. In a follow up study we will look at an application of the model to determine a best management practice to decrease phosphorus transfers while maintaining agricultural profitability.

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6 - ARTICLE IV: PREDICTING THE IMPACTS OF AGRICULTURAL MANAGEMENT PRACTICES ON WATER, SEDIMENTS AND PHOSPHORUS LOADS

Abstract

Problem statement: Shallow soils of Southern Brazil under tobacco cropping are generally potential for degradation environmental contamination, because they are based on inadequate agricultural operations and excessive fertilizer rates application. Changes in management practices may affect water balance, sediment and nutrient loads of agricultural areas. ***Approach:*** This paper evaluates by a modeling approach the impact of farming practices on runoff, sediment and phosphorus loads at Arroio Lino watershed, located in Southern Brazil. This watershed is cropped with tobacco mainly under conventional management system and high fertilizer rates application. The Soil and Water Assessment Tool (SWAT) calibrated model was used to generate a 30-year simulation period. Three scenarios of management practices were tested: conventional tillage (CT), minimum tillage (MT) and no-tillage cultivation (NT) with reduction of 50% of fertilizer rate application. ***Results***: Surface flow decreased when decreasing tillage intensity, but the baseflow increased following almost the same order of magnitude. Hence, the percentage deviation in the water yield is only 6% due to change from conventional tillage to no-tillage management practice. The highest decrease in sediment yield was between conventional tillage scenarios and no-tillage scenarios (66%). The phosphorus loads major change (60%) was due to the decrease (-50%) in the fertilizer rate application instead of due to the change in management practices. ***Conclusion/Recommendations***: No-tillage practices did not significantly affect the water yield, but greatly affected sediment and due to reduction of soil erosion. The soluble P losses increased mainly when the fertilised doses increased. In conclusion it can be stated that conventional tillage practices need to be replaced by less intensive tillage practices in order to minimize environmental impacts caused by a particular land use.

Keywords: Soil erosion, Nutrients, Land use scenarios, SWAT model

6.1 - Introduction

Water availability, water quality and sediment delivery are challenging issues for food supply, food security, human health and natural ecosystems. This is particularly true in a context of global change involving for instance land-use and farming practices (Chaplot et al., 2004).

The combination of inadequate soil use (cultivation on sloping lands and near to water courses) and inadequate management (intensive revolving of soil and low cover levels) with high available phosphorus rates renders the cultivated areas as a great source of sediments (Minella et al. 2007) and phosphorus to the water courses (Pellegrini et al. 2009).

Fertilizer P application together with cropping practices can have a long-term effect on soil fertility and may result in water pollution. Moreover, for the same return period, phosphorus losses were generally greater from plots cultivated up and down the slope than from those cultivated across the slope (Quinton et al., 2001).

The cultivation of tobacco in agricultural highland, involving intensive soil preparation, leads to a great soil erosion and phosphorus transferred to superficial water bodies (Pellegrini et al. 2009).

Conventional tillage tobacco is usually performed using a ridge (*camalhão*) cultivated up and down the slope. The construction of this ridge contributes to the formation of an ephemeral channel flow of rainwater. The concentration of water in these channels enhances soil loss, mainly because there is constant remobilization of soil to eliminate weeds (Antonelli, 2010).

Incompatible agricultural practices with the land use capability of these regions and the application of high fertilizer and pesticide rates make tobacco cultivation an activity with a high contamination risk for water resources in watersheds (Kaiser et al., 2010).

The effect of management systems on soil attributes, sediment movement and organic carbon exportation was evaluated by Mello (2006) in a rural watershed under tobacco crop in Southern Brazil. The most degraded soils were those under conventional tillage. These areas presented the highest soil losses, and also presented the largest sediments movement on the hillslope. Whereas, the conversion to minimum tillage and no tillage systems increased soil quality and reduced sediment delivery.

The main tillage systems of the tobacco crops in Southern Brazil were studied by Pellegrini (2006). The author concluded that soil management systems that include oats as cover crop in winter, using ridge (*camalhão*) and involve minimal soil tillage maintain higher productivity in tobacco reducing losses being more sustainable in the long term.

Water quality models have proven to be a reliable tool for decision making and scenario analysis. The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998) was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in watersheds with varying soils, land use and management conditions (Neitsch et al., 2005). Applications of SWAT model for modeling land use changes and management practices have been expanded worldwide, such as Chaplot et al. (2003); Behera and Panda (2006); Bormann et al. (2007); Ullrich and Volk (2009).

The main objective of this study was to make realistic predictions of the impacts of agricultural management changes on the water balance, sediments and phosphorus loads at the Arroio Lino watershed using the SWAT model.

6.2 - Materials and Methods

6.2.1 - Study area description

The Arroio Lino watershed covers 4.8 km^2 and is located in Agudo County, in the state of Rio Grande do Sul, Brazil. Main soil types (Figure 6.1) are *Chernossolos* (Mollisols) and *Neossolos* (Entisols) (Dalmolin et al., 2004; USDA, 1999). The vegetation is composed by remnants of seasonally deciduous forests in different stages of succession (Pellegrini et al., 2009).

Main land uses in the watershed consist of annual crops, forest, pasture and fallow (Figure 6.2). Almost 30% of the Arroio Lino watershed area is occupied by annual crops and more than 50% by native forest cover (Table 6.1). Approximately 90% of the crop areas are devoted to tobacco production (Pellegrini et al., 2009).

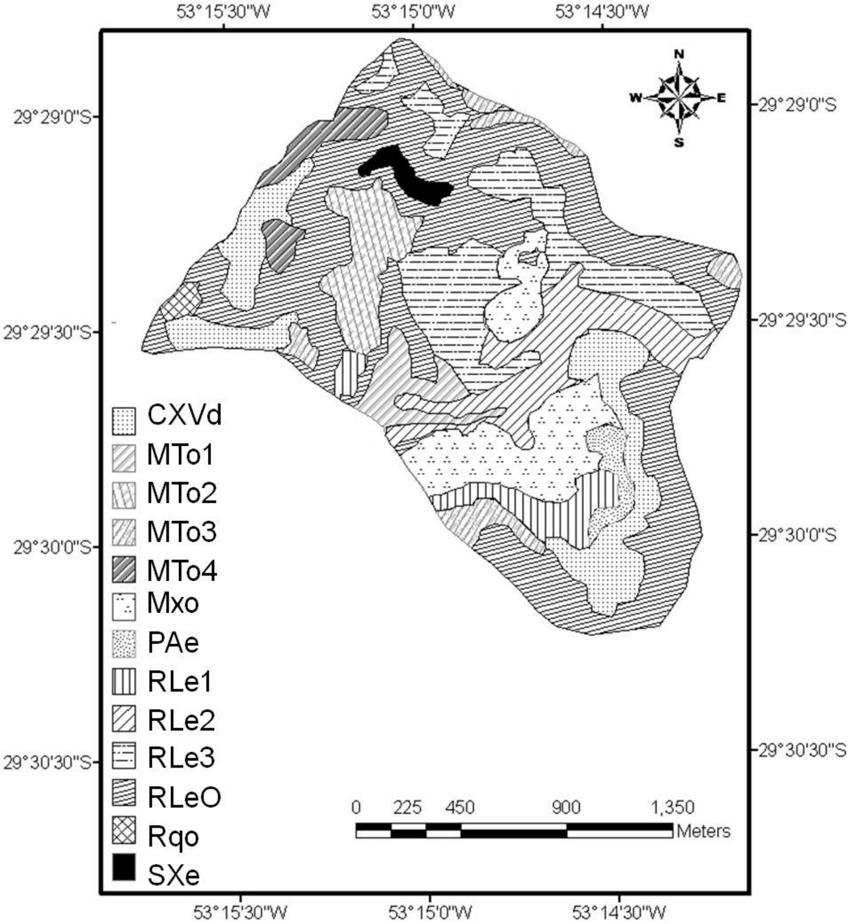

Figura 6.1 – Soil types of the Arroio Lino Watershed.

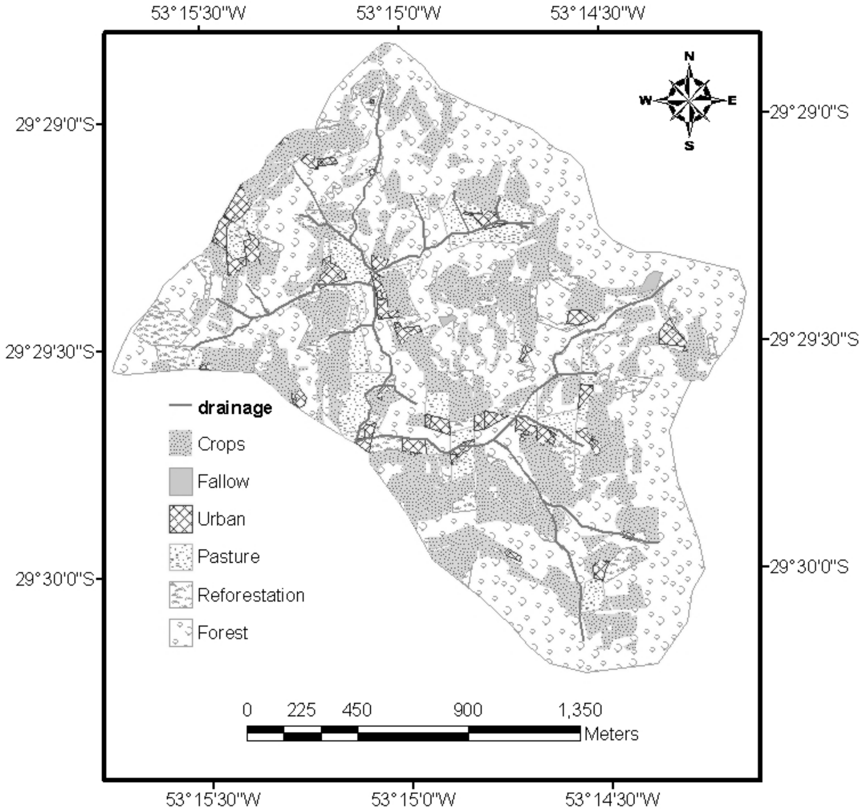

Figure 6.2 – Land use of the Arroio Lino Watershed.

Table 6.1 - Land use classification for the Arroio Lino Watershed

Land Use	Area (ha)	Percent
Tobacco/corn	119.66	24.9
Beans/others	19.20	4.0
Pasture	42.34	8.8
Native forest	259.58	54.1
Exotic forest	25.39	5.3
Urban/roads	13.82	2.9
Watershed	480.00	100.0

Figure 6.3 illustrates a typical tobacco crop in the Arroio Lino watershed. Most of the tobacco crops are cultivated under conventional tillage with intense agricultural exploration which has increased surface runoff and hillslope erosion due to the removal of vegetation. These affects have contributed to excessive sediment and nutrient loads inputs to the streams.

Figure 6.3 – Typical tobacco crop in the Arroio Lino watershed.

6.2.2 - SWAT Model and input data

The SWAT model requires topographic, land use, management, soil parameters input, and weather data. The digital maps (topography, land use and soil types) were processed with a GIS preprocessing interface to create the required model input files.

SWAT simulates a watershed by dividing it into multiple subbasins, which are further divided into hydrologic response units (HRU's). These HRU's are the product of overlaying soils, land use and slope classes.

Land use was determined by field surveys, assisted by a GPS with a GIS software (Pellegrini et al., 2009). A detailed list of agricultural management operations carried out in the watershed with dates and type of operation (planting of crop, tillage, and harvest) was created. In SWAT, the SCS curve number parameter (CN2) is updated for each management operation. The date of operation can vary year to year depending on the cumulative days exceeding the minimum (base) temperature for plant growth. The potential heat units for the crops were calculated and the values were added in the management input file (.mgt file).

The digital soil map (1:15,000) identifies 11 soil types (Figure 3.3), mainly Entisols and Mollisols (Dalmolin et al., 2004; USDA, 2003). The key soil physical properties such as texture percentage (i.e. sand, silt and clay), bulk density, porosity and water content at different tension values (available water capacity) were analyzed for each soil. Additional soil parameters were taken from previous studies developed in the watershed (Rheinheimer, 2003) and assigned to main soil types. The soils information were added in the SWAT user soils databases (.usersoil file).

According to Neitsch et al. (2005) a set of parameters is directly related to the simulations of management practices, such as the biological mixing efficiency (BIOMIX), mixing efficiency of tillage operation (EFFMIX), depth of mixing caused by the tillage operation (DEPTIL), initial SCS runoff curve number for moisture condition II (CN2), Manning's "n" value for overland flow (OV_N), and USLE equation support practice factor (USLE_P).

The biological mixing efficiency (BIOMIX) is the redistribution of soil constituents as a result of the activity of biota in the soil. Studies have shown that biological mixing can be significant in systems where the soil is only infrequently disturbed. In general, as a management system shifts from conventional tillage to conservation tillage to no-till there will be an increase in biological mixing. The efficiency of biological mixing is defined by the user and is conceptually the same as the mixing efficiency of a tillage implement. The redistribution of nutrients by biological mixing is calculated using the same methodology as that used for a tillage operation. If no value for BIOMIX is entered, the model will set BIOMIX = 0.20.

The mixing efficiency of tillage operation (EFFMIX) specifies the fraction of materials (residue, nutrients and pesticides) on the soil surface which are mixed uniformly throughout the soil depth of mixing caused by the tillage operation (DEPTIL). The remaining fraction of residue and nutrients is left in the original location (soil surface or layer).

Initial SCS runoff curve number for moisture condition II (CN2) is a function of the soil's permeability, land use and antecedent soil water. CN2 may be updated in plant, tillage, harvest and kill operations.

USLE equation support practice factor (USLE_P) is defined as the ratio of soil loss with a specific support practice to the corresponding loss with up-and-down slope culture. Support practices include contour tillage, strip cropping on the contour, and terrace systems (Neitsch et al., 2005).

6.2.3 - Land use change and crop management scenarios

After calibration and verification of SWAT model for streamflow (Chapter 3 - Article I), sediments (Chapter 4 – Article II) and phosphorus (Chapter 5 – Article III) different management scenarios were simulated in Arroio Lino watershed.

Three different management systems were considered for the generation of these scenarios: conventional tillage (CT), minimum tillage or conservation tillage (MT) and no-tillage cultivation (NT). The model output variables investigated are surface runoff, baseflow, total water yield, total sediment loading, organic phosphorus, soluble phosphorus, and total phosphorus. Tables 6.2, 6.3 and 6.4 list the schedule management operations and table 6.5 lists the tillage treatments parameters.

Table 6.2 - Schedule management operations for conventional tillage (CT).

Year	Month	Day	Crop	Operation	Description
2	1	29	Tobacco	Harvest and kill operation	
1	7	1		Tillage	Plow and Harrow
1	9	10		Tillage	Ridging plow
1	9	12	Tobacco	Planting	
1	9	12	Tobacco	Fertilizer application	10-18-20, 850 Kg ha^{-1}
1	10	21	Tobacco	Fertilizer application	14-00-14, 200 kg ha^{-1}
1	10	21	Tobacco	Tillage	Plow
1	11	11	Tobacco	Fertilizer application	14-00-14, 200 kg ha^{-1}
1	11	11	Tobacco	Tillage	Plow
1	12	10	Tobacco	Harvest	

Table 6.3 - Schedule management operations for minimum tillage (MT).

Year	Month	Date	Land Use	Operation type	Description
1	1	29	Tobacco	Harvest and kill operation	
1	2	1	Corn	Planting	
1	5	6	Corn	Harvest and kill operation	
1	5	7		Tillage	Plow
1	5	8	Oat	Planting	
1	8	31	Oat	End of growing season	
1	9	1		Tillage	Plow and Harrow
1	9	11		Tillage	Ridging plow
1	9	12	Tobacco	Planting	
1	9	12	Tobacco	Fertilizer application	10-18-20, 850 Kg ha^{-1}
1	10	21	Tobacco	Fertilizer application	14-00-14, 200 kg ha^{-1}
1	10	21	Tobacco	Tillage	Plow
1	11	11	Tobacco	Fertilizer application	14-00-14, 200 kg ha^{-1}
1	11	11	Tobacco	Tillage	Plow
1	12	1	Tobacco	Harvest	

Table 6.4 - Schedule management operations for no-tillage cultivation (NT).

Year	Month	Date	Land Use	Operation type	Description
1	1	29	Tobacco	Harvest and kill operation	
1	2	1	Corn	Planting	
1	5	6	Corn	Harvest and kill operation	
1	5	7		Tillage	Plow and Harrow
1	5	8	Oat	Planting	
1	8	31	Oat	End of growing season	
1	9	12	Tobacco	Planting	
1	9	12	Tobacco	Fertilizer application	10-18-20, 425 kg ha^{-1}
1	10	21	Tobacco	Fertilizer application	14-00-14, 200 kg ha^{-1}
1	10	21	Tobacco	Tillage	Plow
1	12	10	Tobacco	Harvest	

Table 6.5 - Tillage treatments parameters.

Scenario	DEPTIL(mm)[a,b]	EFFMIX[b,c]	BIOMIX[d]	OV_N[b]	CN2[b,d]
CT	300	0.95	0.1	0.09	default
MT	300	0.55	0.3	0.13	-4%
NT	25	0.05	0.4	0.30	-6%

DEPTIL = Depth of mixing caused by the tillage operation; EFFMIX = Mixing efficiency of tillage operation; BIOMIX = Biological mixing efficiency; OV_N = Manning's "n" value for overland flow; CN2 = Initial SCS runoff curve number for moisture condition II; [a] Pellegrini (2006); [b] Neitsch et al. (2005); [c] Behera and Panda (2006); [d] Ullrich and Volk (2009).

6.3 - Results and Discussion

6.3.1 - Climatic Characteristics of the 30-Year Simulation Period

In order to predict future impacts of management alternatives a stochastic weather generator was used to produce a 30-year period of data. Simulated rainfall (PREC), potential evapotranspiration (PET) and evapotranspiration (ET) over the simulated period are presented in Figure 6.4. Annual rainfall ranged between 1145 and 2196 mm year^{-1} with a median and standard deviation of 1686 and 257 mm, respectively.

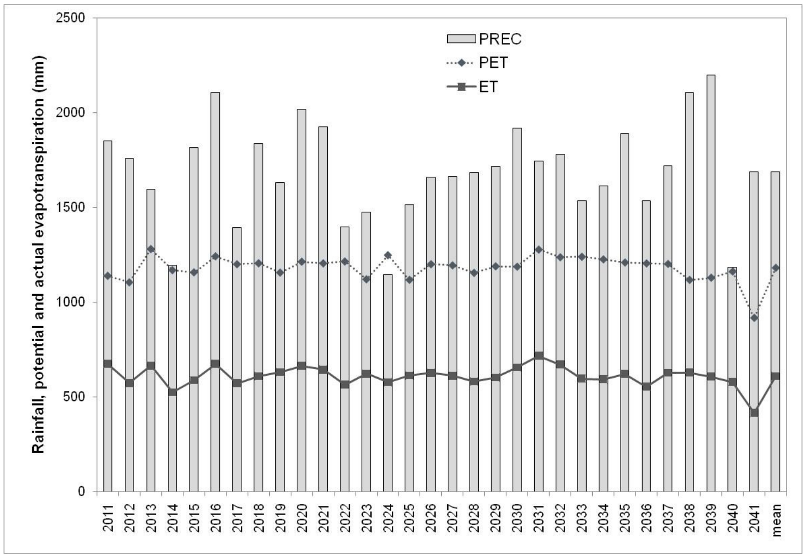

Figure 6.4 – Simulated rainfall, potential evapotranspiration and evapotranspiration over the thirty years period.

6.3.2 - Effect of tillage and fertilizer on runoff, sediment and nutrient losses

Figures 6.5, 6.6 and 6.7 represent the results of simulation of water yield, sediment and phosphorus in the three management scenarios. The surface runoff (SR) decreased when changing from conventional tillage to minimum tillage (CT-MT), minimum tillage to no tillage (MT-NT), and conventional tillage to no tillage (CT-NT). However, the baseflow (BF) increased when decreasing tillage intensity following almost the same order of magnitude that the increases in surface flow. Hence, the percentage deviation in the water yield (WY) is only 6% due to change from conventional tillage to no-tillage management practice.

The highest decrease in sediment yield (SY) was between conventional tillage scenarios and no-tillage scenarios (CT-NT, 66%), followed by conventional tillage to no tillage (CT-MT, 39%) and minimum tillage to no tillage (MT-NT, 28%). Pellegrini (2006) analyzing different management scenarios in plot field scale in Arroio Lino watershed found the same range of variation.

In relation to the soluble phosphorus (Psol), organic phosphorus (Porg) and total phosphorus (Ptot) loads the major change was due to the decrease (-50%) in the fertilizer rate application (CT-NT) than due to the change in management practices (MT-NT and CT-MT). Lessening the P rate by 50% in tobacco fields decreased mean P annual loads by 60%.

Figure 6.8 illustrate the percentage deviation of modeling results regarding to application of management scenarios on water balance components, nutrients and sediment loading. In general the largest differences were between conventional tillage scenarios and no-tillage scenarios.

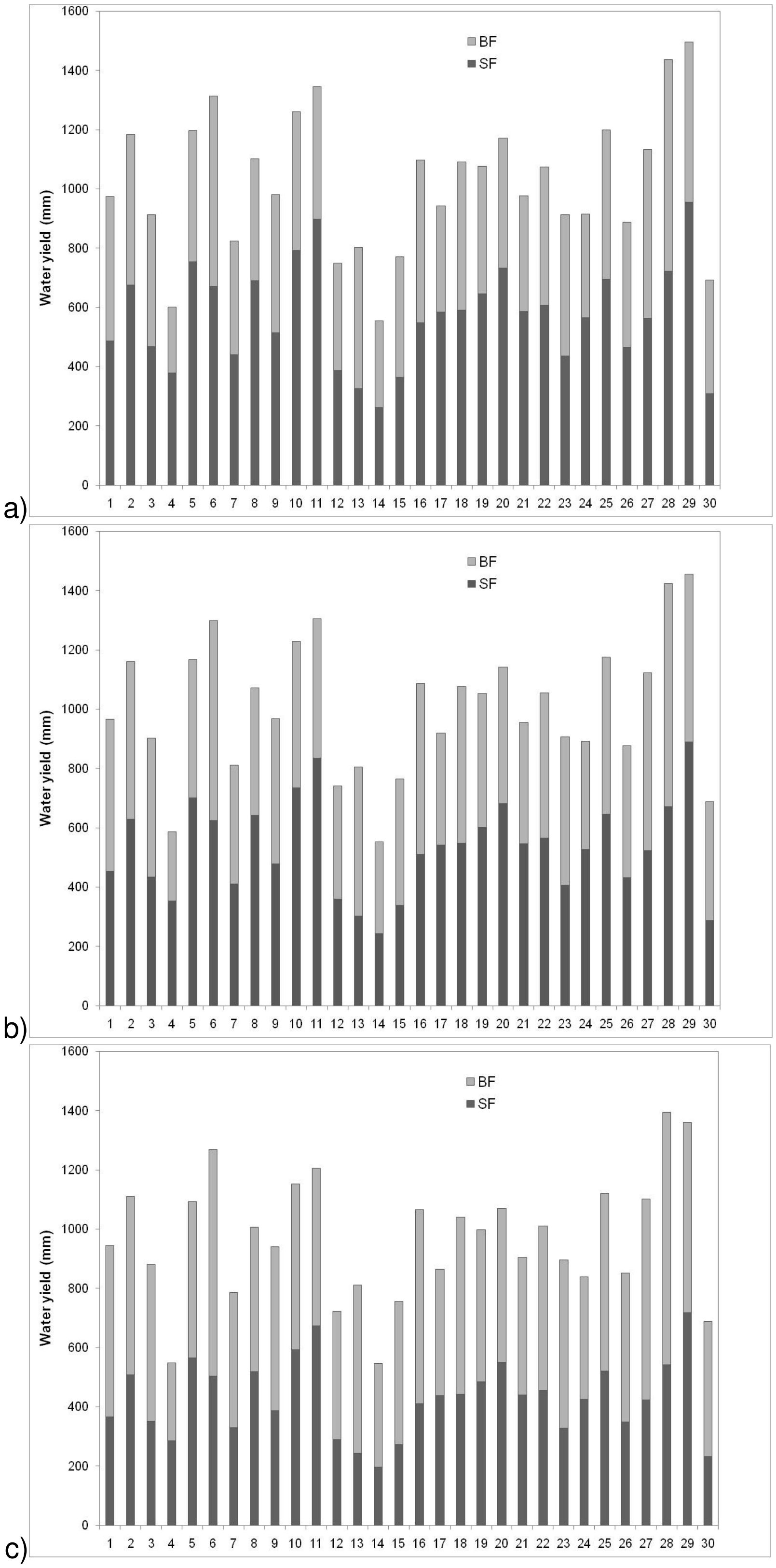

Figure 6.5 – Water yield components results of a) CT, b) MT and c) NT management scenarios.

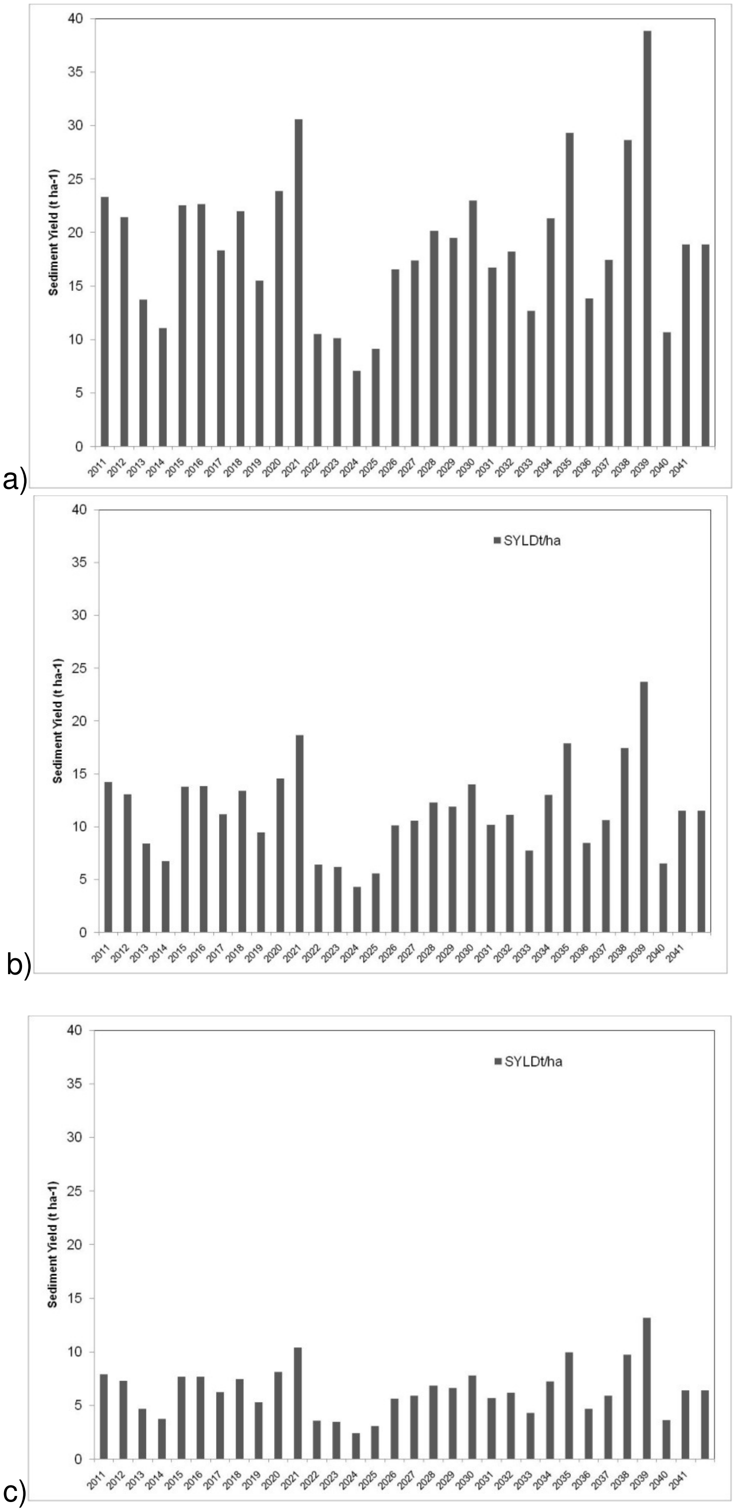

Figure 6.6 – Sediment yield results of a) CT, b) MT and c) NT management scenarios.

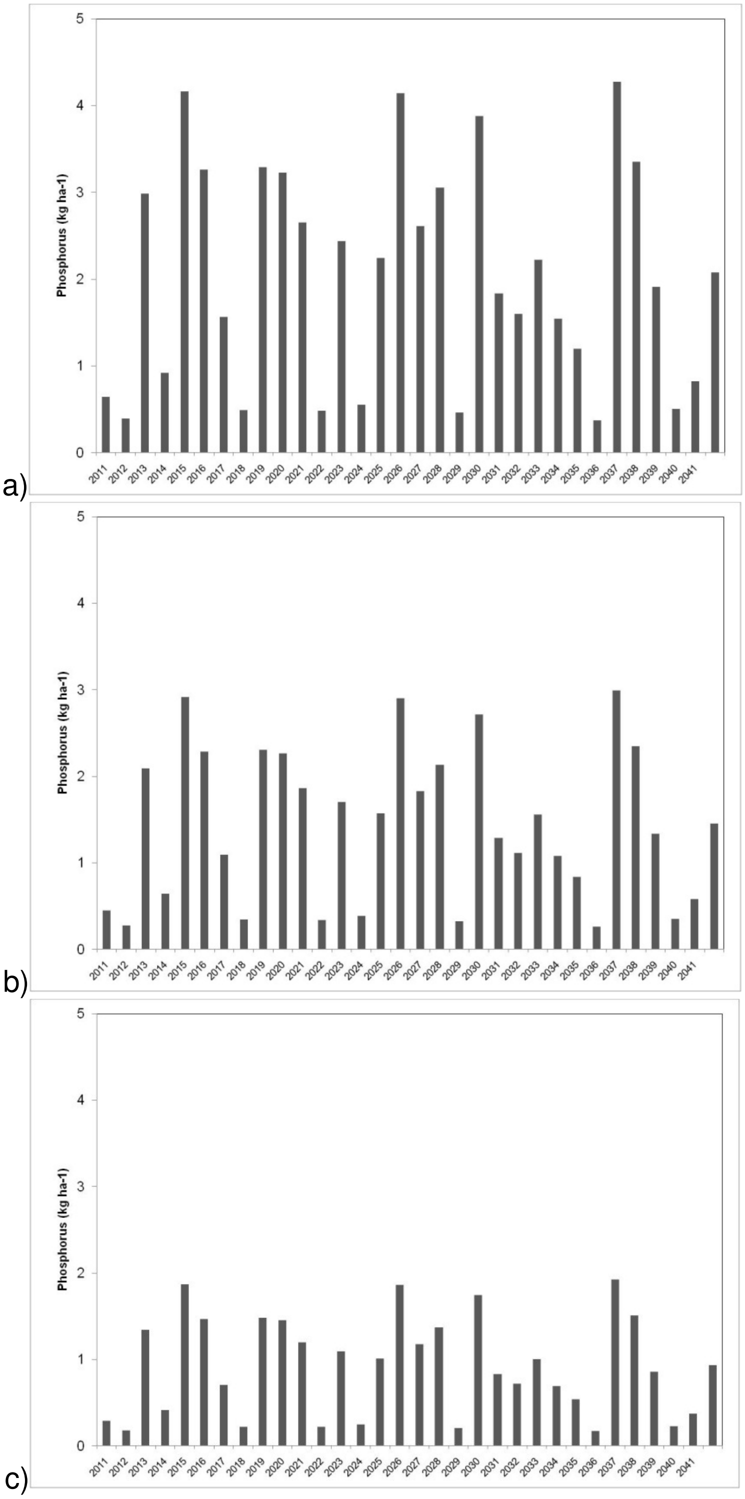

Figure 6.7 – Phosphorus loads of a) CT, b) MT and c) NT management scenarios.

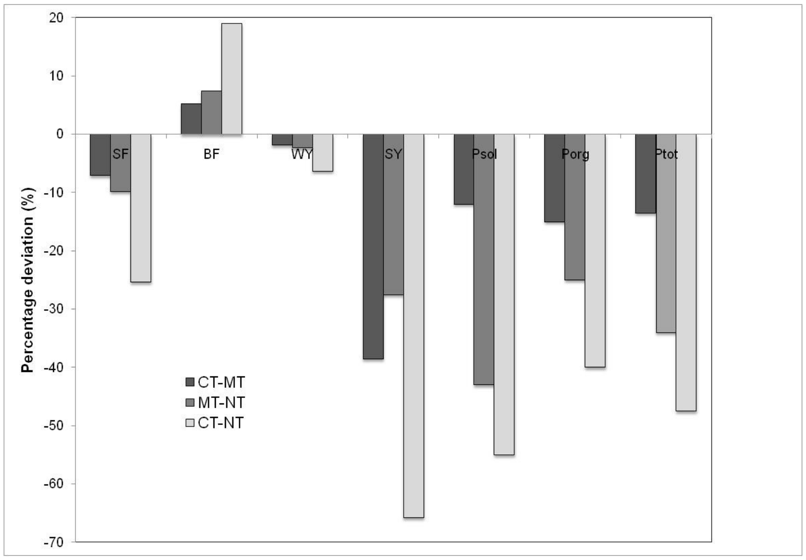

Figure 6.8 – Percentage deviation of modeling results regarding to application of management scenarios on water balance components, nutrients and sediment loading.

6.4 - Conclusions

Three different management scenarios were tested over a 30 years simulated period in the Arroio Lino watershed, in Southern Brazil using the calibrated SWAT.

The scenarios were conventional tillage (CT), minimum tillage or conservation tillage (MT) and no-tillage cultivation (NT) with reduction of 50% of fertilizer rate application. The results suggested that decreasing tillage intensity resulted in an increase of baseflow while surface runoff and total water yield decreased. At the same time sediment and phosphorus loads decreased regarding to the decrease of overland flow and soil erosion.

Data generated with this study, along with the existing ones, support the idea that conventional tillage practices need to be replaced by less intensive tillage practices in order to minimize the sediment yield and phosphorus losses in order to minimize social environmental impacts caused by a particular usage of the land.

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7 - CONCLUSIONS AND RECOMMENDATIONS

Conclusions:

The conclusions, in respect of the performance of the model, include:

- Hydrology: The objective of calibrating and validating SWAT to match the observed flow, within measurement error, was successfully achieved. The results suggest that the SWAT model is a promising tool to evaluate hydrology in subtropical areas, especially in monthly and annual basis.
- Sediments: Initial simulations made with SWAT2009 standard version were not satisfactory even after exhaustive calibration. An attempt was made to include the sediment transport capacity description in the source code of the SWAT model. While neither model performed perfectly, the new SWAT sediment routine was more accurate in modeling sediment yield at the watershed outlet. Additionally, intrawatershed sediment delivery areas were modeled with higher spatial resolution due to the inclusion of the landscape transport capacity as introduced in the sediment deposition routine.
- Phosphorus (P): Five monitoring points of water quality variables were selected in order to assess the ability of SWAT model in simulate P transfers in sub-watersheds with different land use positions in the landscape within the Arroio Lino watershed. The predicted phosphorus loads are in the order of magnitude of the measured ones. However, the model failed to predict the P loads in three sub-watersheds (A1, A2 and B). One potential reason for this failure is that calibration of streamflow and sediment parameters were made only in the watershed outlet, which difficulted the calibration of P related parameters in the sub-watersheds. Another reason could be the SWAT algorithms used for estimate P desorption/adsorption. Finally it was very difficult to evaluate and validate the model performance as the phosphorus sampling was not systematically performed in storm events.

- Management scenarios: The simulation of management practices scenarios confirm the outcome of previous studies indicating that no-tillage practices did not significantly affect the water yield, however, it greatly affected sediment and due to reduction of soil erosion. In conclusion it can be stated that conventional tillage practices need to be replaced by less intensive tillage practices in order to minimize environmental impacts caused by a particular usage of the land.

Recommendations:

For the further improvement of sediment and phosphorus loads simulation in similar watersheds using SWAT model, some suggestions are herein proposed. These include:

- Applying the model to studying watersheds after fragmenting them into smaller units (subbasins and HRU's) in order to have data in different spatial scales.
- Using measured data as input parameters to the model so that the uncertainties can be minimized.
- Perform parameter sensitivity analysis in order to facilitate further calibration and validation.
- Improving the flow simulation in each sub-watershed as much as possible as this is expected to amend the sediment and phosphorus simulation.
- To ensure that the total flow is properly simulated, it must be partitioned into its components (surface flow and baseflow) in order to be separately modelled.
- The calibration of the transport capacity parameters (such as ktc) is a very important issue of SWAT sediment routine that has yet to be adequately solved, so further research is needed.
- The new sediment routine need to be applied and evaluated using other input datasets, and for getting reliable of spatial sediment transport patterns a spatially distributed validation is also desirable.

- Generally, the phosphorus predictions were very sensitive to the parameters related to the soil sorption process. Therefore, the use of non-linear isotherms and sorption parameters that consider soil properties, such as clay mineralogy and Fe content, could improve the SWAT P predictions.
- The lack of sufficient phosphorus data for validation was a challenge in this study and should be addressed further in future studies.
- Many land use and management scenarios could be chosen to be simulated although it is necessary to make predictions that could possible happen in the study area.

The data obtained with the simulation can be used to predict the loss of soil and the transfer of nutrients due to the management system used and also serves to environmental planning. The modeling of sediments and nutrients loads is essential to determine impacts, even before its use in the area of concern in a given crop or agricultural practice. The results of these models along with existing measurements provide clues for the identification of the origin and nature of pollution and for the quantification of its loads. The reliability of the result of the model depends, however, on the overall availability of large amount of data.

The results generated with this study, along with the existing ones, will support the implementation of models that can assist in environmental management and in the choice of economic alternatives that minimize environmental impacts caused by a particular land use.

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