UNIVERSIDADE DE SÃO PAULO

ESCOLA DE ENGENHARIA DE SÃO CARLOS

DANIELLE DE ALMEIDA BRESSIANI

Coping with hydrological risks through flooding risk index, complex watershed modeling, different calibration techniques, and ensemble streamflow forecasting

Corrected Final Version

São Carlos

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Doctoral thesis presented at Escola de Engenharia de São Carlos (São Carlos School of Engineering), of Universidade de São Paulo (University of São Paulo), in partial fulfillment of the requirements for obtaining the Degree of Doctor in Science: Hydraulics and Sanitary Engineering.

Advisor: Prof. Dr. Eduardo Mario Mendiondo
Co-Advisor: Prof. Raghavan Srinivasan, PhD

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Candidata: Engenheira **DANIELLE DE ALMEIDA BRESSIANI**.

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Dedication

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Abstract

Bressiani DA. Coping with hydrological risks through flooding risk index, complex watershed modeling, different calibration techniques, and ensemble streamflow forecasting. Doctoral Thesis, São Carlos School of Engineering, University of São Paulo, São Carlos-SP, Brazil. 2016.

The economic and social losses of environmental disasters are increasingly higher. Floods are a main concern in many locations around the world. Preventive actions are urgent and necessary. This doctoral thesis addresses topics related to hydro-meteorological risks and water resources management. Its aim is to cope with hydrological risks and water resources management through a flooding risk index, complex watershed modeling, different calibration techniques, and ensemble streamflow forecasting. Specific assumptions and research questions are defined in each chapter of the thesis, and are mostly related to the 12,600 km² Piracicaba watershed, in Southeast, Brazil. **Chapter one** has general introductions and explains how the thesis is organized. **Chapter two** brings an assessment and mapping of flooding risks. **Chapter three** reviews the watershed modelling topic, through applications of a selected watershed model (the Soil and Water Assessment Tool - SWAT) in Brazil. **Chapter four** proposes a good practice methodology for calibration of watershed models for different time-steps with available data, having hydrology as main focus. **Chapter five** explores different methodologies for calibrating hydrological models, using two optimization algorithms and with a multi-site and single site approaches to evaluate related changes in performance. **Chapter six** has complex watershed modeling for sub-daily time-step, with an automatic hourly calibration module that was included in SWAT-CUP and the application of these models to forecast ensemble streamflow and with a data assimilation approach with optimization to improve the quality of the forecasts. **Chapter seven** has overall conclusions and **chapter eight** has a summarized list of other activities developed during the doctoral process. Overall we believe the methodologies and results for the Piracicaba watershed are very good. And that they can be replicated in other watersheds in Brazil and around the world. The proposed mapping assessments of flooding vulnerability and risks can be applied for the entire Brazil, and could be used as a tool in water resources management and planning. The watershed model (SWAT) used on this doctoral thesis also proved to be a versatile and robust model, with several good example applications in Brazil, and in particular for the Piracicaba case study. The step by step calibration methodology, as well as the different calibrations performed can help other modelers on choosing where and how to calibrate their own models. For hourly application, this work is pioneer, in area scale and model used. The results for ensemble flow forecasting and data assimilation show a little of what can be performed with this kind of application, and that it can be a potential tool for real time applications in streamflow forecasting and early warning systems. We believe the lessons learnt in this thesis can improve and aid modeler and water resources managers worldwide.

Keywords: Flooding risk index, Brazil mapping SWAT applications, SWAT model, Calibration techniques; Watershed's interior processes, SWAT-CUP hourly module, Ensemble streamflow forecasting, Piracicaba Watershed.

Resumo

Bressiani DA. Lidando com riscos hidrológicos através de índice de risco a inundações, modelagem complexa de bacia hidrográfica, diferentes técnicas de calibração, e previsão de vazões por conjunto. Tese de Doutorado, Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos-SP, Brasil. 2016.

Os prejuízos econômicos e sociais de desastres ambientais têm sido maiores. Inundações são uma das principais preocupações ao redor do mundo. Ações preventivas são urgentes e necessárias. Esta tese de doutorado aborda temas relacionados à gestão dos recursos hídricos e de riscos hidro-meteorológicos. Possui o objetivo de lidar com riscos hidrológicos através de índices de risco a inundações, modelagem complexa de bacias hidrográficas, diferentes técnicas de calibração, e previsão de vazões por conjunto. Pressupostos e objetivos específicos são definidos em cada capítulo da tese, e são na sua maioria relacionados à bacia hidrográfica do Rio Piracicaba (12.600 km²), Sudeste do Brasil. O **Capítulo um** traz as introduções gerais e explica a organização da tese. O **capítulo dois** desenvolve mapeamento de riscos a inundações. O **capítulo três** revisa o tópico de modelagem de bacias hidrográficas, através de aplicações de um modelo selecionado (*Soil and Water Assessment Tool* - SWAT) no Brasil. O **quarto capítulo** propõe uma metodologia de boas práticas para a calibração de modelos de bacias hidrográficas utlizando dados disponíveis, com foco principal na hidrologia. O **capítulo cinco** explora diferentes metodologias de calibração, utilizando dois algoritmos de otimização e abordagens de calibração em um local e demais locais para avaliar alterações relacionadas ao desempenho da modelagem. O **capítulo seis** trabalha com modelagem sub-diária, com um módulo de calibração horária automática, que foi incluído no SWAT-CUP, e aplicação destes modelos para previsão de vazões por conjunto e assimilação de dados com otimização, para melhorar a qualidade das previsões. O **sétimo capítulo** traz as conclusões gerais da tese e **oitavo capítulo** apresenta uma lista resumida de outras atividades desenvolvidas durante o doutorado. Acreditamos que as metodologias e resultados para a bacia hidrográfica Piracicaba são muito bons. E que podem ser replicados em outras bacias hidrográficas no Brasil e ao redor do mundo. O mapeamento de vulnerabilidade e riscos de inundação propostos pode ser aplicados para todo o Brasil, além de possuir potencial como uma ferramenta de planejamento. O modelo utilizado (SWAT) também provou ser versátil e robusto, com vários bons exemplos de aplicações no Brasil, e em especial para a Bacia do Piracicaba. A metodologia sistemática para calibração, bem como as diferentes calibrações executadas podem auxiliar outros modeladores a escolherem como calibrar seus próprios modelos. Este trabalho é pioneiro no tipo de aplicação horária apresentada. Os resultados de previsão por conjunto de vazões e de assimilação de dados mostram o potencial da metodologia para sistemas de previsão de vazões em tempo real e em sistemas de alerta antecipado. Nós acreditamos que as lições aprendidas nesta tese podem auxiliar modeladores e gestores de recursos hídricos ao redor do mundo.

Pavras-Chave: Índice de risco a inundações, Mapeamento de Aplicações do SWAT no Brasil, Modelo SWAT, Técnicas de calibração, Processos internos de bacias hidrográficas, Módulo horário para o SWAT-CUP, Previsão de vazões por conjunto, Bacia Hidrográfica do Rio Piracicaba.

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1. General Introduction

The economic and social losses of environmental disasters are increasingly higher. Floods are a main concern in many locations around the world. Preventive actions are urgent and necessary in an integrated way for watersheds. With climate change projections, the probability of severe and extreme events increase, intensifying the need for a better understanding of water resources dynamics, flood risks and flood forecasts. Effective forward planning is crucial to implement a better management of water resources and disaster management due to floods.

Brazil copes with several water resources, flooding and risk management challenges and is somewhat conscious of them, and therefore to address them has established guidelines and policies. This doctoral work is in agreement with the objectives of Brazil’s federal laws: law 9,433 of 1997, which institutes the National Water Resources Policy and creates the National Water Resources Management System. Law 11,445 of 2007 that establishes national guidelines for basic sanitation, and its universal access, as also addresses urban waters. Law 12,187 of 2009, which establishes the National Policy on Climate Change, which includes the promotion and development of scientific research to identify vulnerabilities and adopt adaptation measures. And law 12,608 of 2012, which establishes the National Policy on Protection and Civil Defense, and authorizes the creation of a disaster’s information and monitoring system, stating that all governing levels have the duty to adopt the necessary measures to reduce disaster risks and that the uncertainty regarding the disaster risks shall not constitute an obstacle for the adoption of preventive and mitigating measures to reduce those risks.

Aware of those problems in Brazil and around the world, and with the intention to develop and analyze ways to address and deal with these topics, this doctoral thesis addresses topics related to hydro-meteorological risks and water resources management. Its aim is to cope with hydrological risks and water resources management through a flooding risk index, complex watershed modeling, different calibration techniques, and ensemble streamflow forecasting.

Integrated water resources management (IWRM) is a very complex task. This thesis intends to collaborate with a holistic approach, and integrated thinking to aid with conceptual basis, tools, mappings, and watershed modelling for different time-steps and scales and scientific contributions. Geographical Information Systems (GIS) and watershed models are important tools for IWRM. It is known that these tools wont by themselves address the faced challenges, but they can provide support for a better IWRM. Therefore, improved tools and proven concepts are needed, especially with the growing pressure on the water resources and increased hydro-meteorological risks. The watershed model used in this thesis was chosen exactly for its ability to deal with a diversity of watershed and water resources facets. Even thought, some aspects of the model were more addressed than others, its versatility and possibility of future work on different IWRM aspects was appealing.

The specific studies presented in this thesis have as main focus the Piracicaba watershed in southeast Brazil. The 12,600 km² Piracicaba watershed is part of the Tietê and Paraná watersheds. It is a very relevant watershed for supplying water to the São Paulo Metropolitan Region, and for its diverse land uses and urban areas (in which about 3.5 million people live). It is also a very relevant due to its high hydrological variability.

The chapters follow the intuitive flow of the student's learning process. Starting with an assessment and understanding of flooding risks (Chapter two); entering and reviewing the watershed modelling topic, through applications of a selected watershed model in Brazil (Chapter three); following in the understanding, as well as proposing a good practice step-by-step methodology for calibration of watershed models for different time-steps with available data, having hydrology as main focus (Chapter four). Exploring more the calibration world, trying to understand and test different calibration techniques in a multi-site and single site approaches to view the changes in performance and in model response (Chapter five). At last to perform sub-daily modeling with an automatic hourly calibration module; and use these models aiming to provide ensemble streamflow forecasts (Chapter six).

More specifically chapter two aims to assist in planning and building up resilience, by establishing and applying a flood risk assessment methodology, through a spatial flood risk index and related vulnerabilities, hazard and exposure. This methodology was applied for the Piracicaba, Capivari and Jundiaí (PCJ) watersheds, in southeast Brazil. These indices bring several layers of information and there are unbridgeable uncertainties in the process. However, we believe the methodology, integration of the components and mappings can be important instruments for improving planning and for reducing and managing flood disaster risks.

The third chapter aims to discuss and review, as part of an extensive survey, watershed model applications in Brazil, with the particular focus on the ecohydrological watershed-scale model: Soil and Water Assessment Tool (SWAT), which was the model chosen as main tool for this doctoral work. Temporal and spatial distributions, a summary of hydrologic calibration and validation results and a synopsis of the types of applications that were performed are reported for the surveyed studies. Data issues and different data sources for Brazilian model applications were also presented. It brings a discussion on future research needs and directions for watershed and hydrologic modelling and water resources management in general. Providing a conceptual baseline as well as an understanding of all of what was done in Brazil with SWAT and main hindrances and possibilities in the future.

The fourth chapter proposes a systematic calibration methodology, with a step-by-step approach, to take into consideration different watersheds' dynamics in the calibration process and to assist modelers in developing their validated models for their watershed management goals. The Piracicaba watershed case study was successful in demonstrating the broad methodology, as well as in discussing the specifics of the chosen methodologies and calibration steps. Input and output uncertainty analysis was done, showing the non-uniqueness of calibration results.

The fifth chapter aims to test different methods for flow calibration, to try to understand how much of an increase on model performance efficiency, and decrease of processing time, can be obtained with different calibration techniques. Therefore two different methods were chosen: a supervised calibration using a local optimization algorithm: the Sequential Uncertainty FItting (SUFI-2) and also a global optimization algorithm: Particle Swam Optimization (PSO). Also this study aims to see how much of a difference in a diverse watershed the interior processes have in the calibration process, therefore, two different daily streamflow calibrations were performed: 1) only for the most downstream gauge station of the watershed; 2) in three different regions with similar physical characteristics (land use, geomorphology and climate).

The sixth chapter of this thesis aims to provide a framework for streamflow forecasting using ensemble Numerical Weather Prediction data, a semi-distributed process-based hydrological model at daily and hourly time-steps and data assimilation with optimization, to support early flood warning systems. Specifically, the objectives of this chapter are to: (1) develop a new module to allow automatic calibration of flow for SWAT at hourly time-step on SWAT-CUP; (2) assess the sensitivity of different parameters at different time-steps: monthly, daily and hourly and perform one-at-a-time sensitivity analysis of several parameters at hourly time-step; (3) perform SWAT streamflow calibration and validation for a large watershed in southeast Brazil (Piracicaba watershed) at hourly time-step; (4) integrate ensemble numerical weather forecasts as input to hourly and daily calibrated SWAT models to forecast streamflow; (5) develop a framework with data assimilation for streamflow forecasting using ensemble NWP, SWAT and SWAT-CUP optimization to support future real-time flood warning systems.

The seventh chapter brings few general conclusions of the thesis. Thus, the major objective of this thesis was to contribute to water resources management; hydro-meteorological and flooding risks management; watershed and hydrological modeling; and streamflow forecasting. Specific assumptions and research questions are defined in the chapters, which were published; are in the review process; or will be soon submitted to peer-reviewed international journals.

It is important to stress that this doctoral work was developed from a research process and by activities developed in Brazil, United States, France and Switzerland, counting with the contributions of several others. Other products were generated and were important for the development of this thesis and for the student, including: published papers, oral presentations in international and regional conferences, conducted courses, conference publications, participation in research projects, organization of conference and workshops, etc. These different important steps of the way were summarized in chapter eight.

2. *Flooding Risk Assessment: risk, vulnerability, hazard and exposure spatial indexes*

A modified version of this chapter will be shortly submitted to a peer-review international journal, with the following co-authors: Bressiani, D.A.; Mendiondo EM, Srinivasan, R.

Abstract

The economic and social losses of environmental disasters are increasingly higher. The perspectives of global changes, which include hydro-meteorological extreme events with higher frequency and magnitude only exacerbates the complexity of an already critical scenario. Assessments of flooding risks and the understanding of its components are crucial for society; they enable the identification of their shortcomings and possibilities of adaptation in face of extreme events. This chapter aims to contribute to those tasks, assisting decision makers in planning and building up resilience, by establishing and applying a flood risk assessment methodology, through a spatial flood risk index. This methodology was applied for the Piracicaba, Capivari and Jundiaí (PCJ) watersheds, in southeast Brazil. Risk comprises different types of potential losses, which are difficult to quantify, but can be assessed and mapped with knowledge of the hazards, population and socio-economic development. In this study, risk comprises three main components: hazard, exposure and vulnerability. Each of the three components was assessed, as risk in itself. The vulnerability component encompasses management, socio-economic and environmental vulnerabilities. It is important to stress that, due to unbridgeable uncertainties, some decisions had to be made. However, if used carefully, methodology, integration of the components and mappings are decisive instruments for improving urban planning and for reducing and managing flood disaster risks.

Keywords: Hydro-meteorological risks, flooding risk index, mapping vulnerability, exposure and hazard;

2-1. Introduction

Global annual economic losses associated with environmental disasters have increased. According to the United Nations[1], the amount of gross domestic product (GDP) exposed to damage from disasters increased from $ 525.7 billion in the 70s to $ 1.58 trillion in the present day[1]. Data from Munich Re (insurer) also states the increase of economic damage due to disasters: in the 50’s, the damage amounted to US $ 48.1 billion in losses to those directly or indirectly affected, a figure which rose to US $ 728.8 billion in the 90's. In 2010, alone, the damage amounted to US $ 150 billion[2,3].

The frequency of hydro-meteorological disasters has also increased. The number has more than doubled between 1991 and 2000. In this same decade, the number of people reported killed by hydro-meteorological disasters was 600,000. Within this picture, floods represent two-thirds of the disasters’ affected people and 15% of the resulting deaths[4].

The situation of developing countries, more vulnerable in this regard, is particularly alarming. More than 95% of disasters’ related deaths take place in these countries[4,5]. This situation occurs, among several factors, because of greater vulnerability, related especially to: socio-economic and management factors; the lack of preparation when disasters strike, that is, the absence of effective early warning systems and response systems, with a trained and organized front constituted of population and civil defense; but also due to lack of disaster preparedness and knowledge, with insufficient planning and zoning of flooding risk areas. Brazil is a country vulnerable to environmental disasters, among which floods stand out, with 58% of all disasters. In São Paulo state alone, the number of people affected by floods (abrupt and gradual) between 1991 and 2010 was approximately 3.75 million[6].

With regard to environmental disasters, urban areas with high population concentrations have an even more complex situation. In addition to altering the hydrological cycle and increasing flooding risk, they increase the environmental and social vulnerabilities of the watershed to flooding and create a challenge for disaster risk management and planning[7]. In Brazil, as in most of the developing countries, most urban areas went through a very rapid population growth, which was not accompanied by adequate urban and environmental planning[8].

The storm that struck in the mountainous region of Rio de Janeiro state, in January of 2011, where in 24 hours rained the expected for the entire month, resulted in a hydro-meteorological disaster. The numbers received by Rio de Janeiro's Civil Defense by February 9, 2011 were of: 172,259 affected people, 14,106 made homeless; 23,353 displaced and 886 deaths. This environmental disaster has shown Brazil the need to change the means to manage risk and disaster. Following this sad event, the Federal Government established the National Plan for Risk Management and Response to Natural Disasters, which made the issue a priority on the political agenda, with four major lines: prevention; mapping; monitoring and early warning; and response.

Floods induced by extreme precipitation events are a main concern in many locations around the world[9,10,11], making preventive actions urgent and necessary in an integrated way for watersheds[12,13]. With climate change projections the probability of severe and extreme events increase[14], intensifying the need for a better understanding of flood risks and flood forecasts[11,16]. Effective forward planning is crucial to implement disaster management due to floods[11,15,16,16].

This chapter, as the entire thesis, follow the Sendai Framework for Disaster Risk Reduction 2015–2030, adopted at the Third United Nations World Conference on Disaster Risk Reduction, held in March/2015 in Sendai, Japan[18]. This Framework established four priority areas for disaster risk reduction: 1) understanding disaster risk; 2) strengthening disaster risk governance to manage disaster risk; 3) investing in disaster risk reduction for resilience, and 4) enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction. This chapter focuses more on the first priority, while the following (that culminate in the 6th) focus on the 2nd priority, building up tools and methodologies for disaster risk management (watershed modeling and flood forecasting), to reduce vulnerability and exposure and therefore reduce disaster risk.

In this context, an integrated and system based approach for water management, with comprehensive and flexible adaptation and planning measures, is necessary. It is essential to implement an hidro-meteorological and climate risk management to ensure sustainable interventions, to reduce the risk of hydrological disasters and to build resilience[15,16,19]. Resilience is the ability of a system to resist, change or adapt to reach a new level of acceptable operation[5,20]. The need to make society more resilient to environmental disasters, floods and climate change is clear, as the need to develop decision support tools and methodologies that provide a better integrated water and disaster management.

Reducing vulnerability to environmental disasters is an urgent matter, that requires a better understanding of the vulnerability' extent and location of systems[21], especially in developing countries and their cities and should be a priority of sustainable agenda[22,23]. It is better and cheaper to invest in hydro-meteorological risk management, to better combat disasters, reduce impacts and vulnerabilities, than to suffer their consequences unprepared[24].

Thus, it is understood that a first step in this process is flood risk mapping and assessment. The understanding of the components that influence risk and its composition is critical for stakeholders to identify shortcomings and to better adapt to flooding risks. In Brazil, many cities, which are still growing, already suffer from floods and its high social-economic impacts, but also have space and opportunity to adapt better to extreme events and to reduce their vulnerability, exposure and associated risks. With an aim to assist in the planning and identification of adaptation strategies, this chapter establishes and applies a mapping methodology of flood risk assessment. It proposes and applies a methodology to map and assess the risk components and integrates them into a risk assessment, with a spatial risk index, aimed to aid better planning and troubleshooting. The chosen study area is the Piracicaba, Capivari and Jundiaí (PCJ) watersheds, which harbor several medium to large size important cities and flooding issues.

2-2. Methodology

2-2.1. Study Area

This study was conducted for the PCJ watershed, composed by three main rivers and basins: the Piracicaba, Capivari and Jundiaí river basins. The PCJ watershed has about 15,300 km², being located in the states of São Paulo (SP) and Minas Gerais (MG). The Piracicaba River

Basin has approximately 12,600 km² and 4 million of people. It consists of five sub-basins: Atibaia, Camanducaia, Corumbataí, Jaguarí and Piracicaba. The Capivari River Basin has approximately 1,600 km² and the Jundiaí River Basin has about 1,100 km². The PCJ is in the middle part of the Tietê watershed, which is, in turn, part of the Paraná watershed.

PCJ is predominantly rural, although there are important urban areas: with about 10% of São Paulo state's population, there are medium to large size cities close to the main river, such as Campinas, Piracicaba, Americana and Jundiaí. There are a total of 60 municipalities included in PCJ, with a population of approximately 5.15 million people. The watershed in highly relevant for these factors, as well as for providing water supply for the Metropolitan Region of São Paulo and for having a very active and articulate federal watershed committee and state management units (UGRHI-5 in SP and UPGRH - PJ1 in MG)[25]. The watershed and its municipalities and sub-basins can be seen in Figure 2-1.

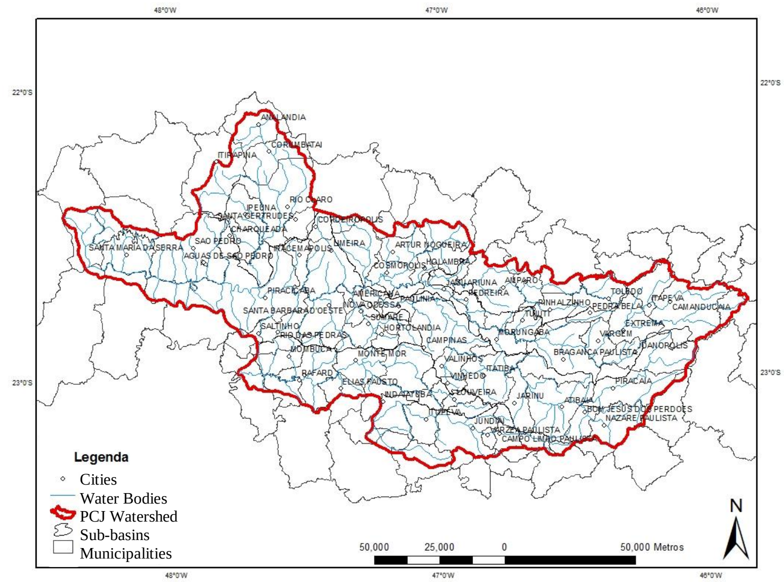

Figure 2-1- Piracicaba, Capivari e Jundiaí (PCJ) Watershed (Sources: Water Bodies 1:100000 Municipalities[26], watershed limits[26]

2-2.2. Risk Index (I_{risk})

Risk is related to the resulting detrimental consequences from the likelihood of occurrence of an adverse event in relation to the system's vulnerable condition. Risk can be described as a function of three components: hazard, element in risk (or exposure) and vulnerability[27,28]. We follow the hypothesis that risk has a multiplicative formulation, since all of the three components are needed for risk to exist. For that reason, the equation used here is the one proposed by Peduzzi et al.[28] and Mendiondo[5] (Equation 1).

$$Risk = Hazard * Exposure * Vulnerability \qquad (1)$$

For each risk component a methodology was developed. Each index, sub-divisions (indicators) and parameters used for calculations are presented in Table 2.1.

Table 2-1. - Indices and parameters used for its composition

Index	Indicators		Parameters Considered	Data Sources	Data Period
Hazard (Ihaz)			Maximum Precipitation over a day Annual Averages of Maximum Precipitations over a day Maximum Precipitation over 3 days Average number of days in a year with precipitation between 25-50 mm Average number of days in a year with precipitation greater than 50 mm	DAEE and ANA	2004-2012
Vulnerability (Ivul)	management vulnerability (ivmgt)		Municipal Risk Reduction Plan Programs and/or actions on riskmanagement Municipal Habitation Plan Sanitation Policy If the policy is instituted by law or not If the policy covers drainage and management If the policy covers solid waste management Sanitation Plan If the Sanitation Plan is regulated If the Plan covers drainage and management If the Plan covers solid waste management	Municipalities Profile-Brazilian Institute of Geography and Statistics - IBGE (2012)	2011
	environmental (ivmgt)		Land Use	PCJ (2003) and Laurentis (2012)	2002, 2010
			HAND - Height Above the Nearest Drainage	Prepared based on DEM from SRTM and EMBRAPA (2005)	2001
			Slope		
	socioeconomic vulnerability (ivsoc)	HDI (ivhdi)	Human Development Index (HDI)	UN Development Program (PNUD, 2000)	2000
		Income (ivsinc)	Household monthly nominal income per capita	2010 Demographic Census (IBGE,2011)	2010
		Literacy (ivslit)	literate people over 5 years Number of residents over 5 years Households' responsibles literate Number of responsibles		
		Age (ivsage)	Number of residents Number of people with determined age		
		habitation (ivshab)	Permanent Private Households (PPH) PPH private owned and settled PPH suitable PPH semi-suitable PPH not suitable		
Exposure (Iexp)			Population Area of the region		

The hazard index (I_{haz}) comprises characteristics from the extreme precipitation events, related to the maximum values and frequency of occurrence. The exposure index (I_{exp}) is made of the number of people in a particular area. The vulnerability index (I_{vul}) consists of three indicators: indicator of vulnerability related to management ($i_{v_{mgt}}$); environmental vulnerability indicator ($i_{v_{env}}$); and socioeconomic vulnerability indicator ($i_{v_{soc}}$). The management vulnerability indicator ($i_{v_{mgt}}$) is calculated according to the existence of a municipal risk reduction plan; programs and/or action for risk reduction and management; habitation plan; sanitation plan and policy. The environmental vulnerability indicator ($i_{v_{env}}$) is based on the areas close in height to a river, and to the slope, crossed with the land use.

The socioeconomic vulnerability index was developed to encompass five indicators: habitation ($i_{v_{shab}}$); income ($i_{v_{sinc}}$); literacy ($i_{v_{slit}}$); age ($i_{v_{sage}}$) and the Human Development Index (HDI) ($i_{v_{shdi}}$). One interesting aspect of this methodology is its capacity to accommodate all these indicators and indices, aside of also including the management component, which is critical to understand vulnerability. A summary of the composition of these indices is at Table 2-1; the specific methodologies are explained in the following sections.

Different GIS (Geographic Information System) softwares were used on this chapter. The operations and integration of indices and indicators were conducted on ArcGIS® 9.3 [29], as was the interpretation and analysis of the spatialized distribution of the indices and indicators. Idrisi 32[30] was also used to cross and reclassify the two land use maps; *ENVI 4.7* (*IDL* 7.1)[31] was used to apply the HAND algorithm [32,33].

2-2.3. Hazard Index (I_{haz})

The hazard index is based on data from 55 precipitation gauge stations in the study area. Data was made available by the Department of Water and Electric Energy (DAEE) (40 gauges) and by the Brazilian National Water Agency (ANA) (15 stations) for the period of 2004-2012.

In order to incorporate the high intensity, extreme precipitation events, and to give the magnitude of the hazard (rainfall event), the following parameters were chosen: maximum one and three days precipitations in the period, and the annual average maximum rainfall over a day.

Nonetheless, to include not only maximum values, the frequency of precipitation events was included. It was based on the annual average of number of days with precipitation between 25 and 50 mm, and the annual average of number of days with precipitation above 50mm (Table 2-1). These parameters were established to capture the magnitude and frequency of the high intensity rainfall events. They were based on Jiang et al.[34] that used the maximum precipitation in 3 days and the number of storms per year. These values were standardized in a compatible measure with fuzzy inference, with the use of a sigmoidal function to normalize the values on a 0 to 1 scale. These functions need coefficients, as control points that define the maximum (b) and minimum (a) for standardization: Equation 2[35]. This function was chosen because it is more sensible to high magnitude and frequency rainfall values.

$$\mu(x) = \begin{cases} 0, & if\ \ x < a\,; \\ \cos^2 \alpha\,,\ \ e\ \alpha = (1-(x-a)/(b-a)) * \frac{\pi}{2}, & if\ \ x \geq a\ e\ x \leq b\,; \\ 1, & if\ \ x > b, \end{cases} \tag{2}$$

The maximum (b) and minimum (a) coefficients selected for the precipitation over a day (for the maximum and for the annual average of maximums) were stipulated as 50 mm (a) and 100 mm (a) for 3 days; for the maximum (b), the larger values found in each sample were used. The number of events with determined rainfall (a) was set as zero days, the maximum (b) was set to 25 days (for rainfall between 25-50mm) and to 35 (for rainfall above 50 mm).

To combine these different parameters into the hazard index, different weights were given through the Analytic Hierarchy Process (AHP)[36]. This method is based on a square matrix of the parameters used, in which every matrix element (a_{ij}) is the relative importance of one parameter in relation to the other[36,37]. A Consistency Ratio (CR) can be calculated with this method, to verify the degree of consistency in the comparison. CR should be less than 0.1 to matrices of six elements or smaller [36].

The values of maximum precipitation over a day were considered the most important parameter for flood risk, since they give the idea of intensity and magnitude, followed by average annual maximum precipitation over a day, which brings an average magnitude and a sense of frequency. The maximum precipitation in 3 days was considered third in importance, since in longer time-frames, usually the forecasts are better, therefore prevention can be taken in advance and response can occur during the event, at least more than in a rapid and intense episode.

The parameters related to frequency of rainfall were considered less important compared to the magnitude ones. In this regard, the average number of days with precipitation above 50mm was considered more significant, and then the ones with rainfall between 25 and 50mm. The hazard index was spatialized using Thiessen polygon method[38] in ArcGIS® 9.3 [29].

2-2.4. Exposure Index (${I_{exp}}$)

The exposure index (I_{exp}) is based on the number of exposed people in a certain area; this demographic was done using the census data per census designated region [39]. Given the distributions of demographic values found, they were normalized by a reclassification based on interval value bands: Eq. 3. The demographic was used since the census designated regions have very different area sizes. Jiang et al.[34] and Peduzzi et al.[40] used similar parameters to define their exposure component for risk assessments.

$$I_{exp} = f\left(\frac{Pop}{Area}\right) = f(d) = \begin{cases} 0,05; & if\ d < 0,001 \\ 0,1; & if\ d < 0,005 \\ 0,2; & if\ d < 0,007 \\ 0,3; & if\ d < 0,01 \\ 0,5; & if\ d < 0,02 \\ 0,6; & if\ d < 0,03 \\ 0,7; & if\ d < 0,05 \\ 0,8; & if\ d < 0,1 \\ 0,9; & if\ d < 0,5 \\ 1,0; & f\ d < 10 \end{cases} \tag{3}$$

2-2.5. Vulnerability Index (${I_{vul}}$)

Vulnerability is a combination of complex dynamic and interrelated factors, it is function of character, magnitude and rate of change to which a system is exposed; it corresponds to the systems' sensitivity and capacity to adapt[5]. The vulnerability index (I_{vul}) encompasses three main indicators: vulnerability indicator related to management ($i_{v_{mgt}}$); environmental vulnerability indicator ($i_{v_{env}}$); and socioeconomic vulnerability indicator ($i_{v_{soc}}$).

2-2.5.1. Vulnerability indicator related to management $(\boldsymbol{i}_{v_{mgt}})$

We consider the need of a vulnerability indicator related to management very high, especially considering the Brazilian scenario, in which one location or city may have a flood risk plan and a very organized strategy, and others may not be organized on this matter at all. Management is important to put in place mitigation and adaptation strategies to floods, such as: early warnings, flood insurance, evacuation plans, trained civil defense, preservation of the riparian and wetland areas, linear parks, municipal zoning, among others, which have significant influence in the degree of a system vulnerability to flooding and high intensity precipitation events. A similar indicator was found only in Isnard et al.[41], that analyses risk assessment of hurricanes. Many other studies related to vulnerability assessments and/or flooding or hydro-meteorological disaster's risks do not include this management aspect[34,28,42,43,44].

This is an indicator hard to assess and we had to rely on the available data. This indicator was elaborated based on information available at the municipal level from the Survey of Basic Municipal Information - Profile of Municipalities 2011[39]. The parameters used were the ones deemed important in relation to flooding risk. The parameters considered were: the existence of a Municipal Plan for Risk Reduction; of programs or actions on landslides' risk management and on preventive environmental preservation and recovery; of Municipal Housing Plan; and of a sanitation factor.

The sanitation factor was based on the Sanitation Policy, the factors considered were: its existence or not; if this policy is established by law; if it includes drainage and management, as well as solid waste treatment; and the same for the Sanitation Plan. Since these are qualitative not quantitative values, a 0 to 1 classification was proposed. All the parameters considered and how they were classified are presented on Figure 2-2.

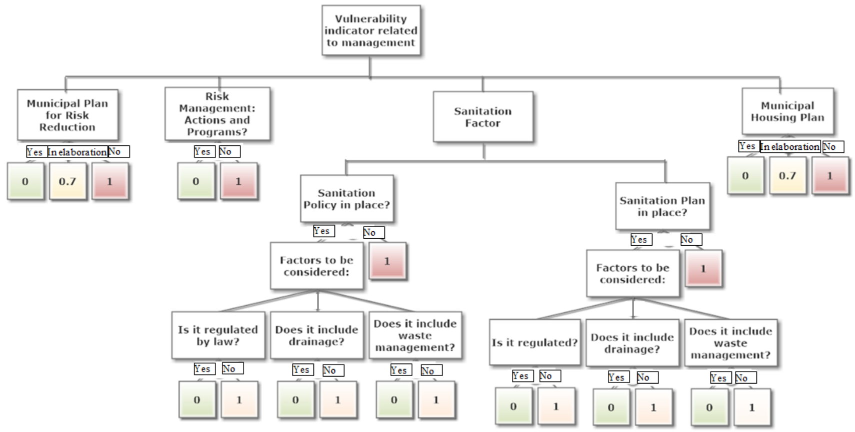

Figure 2-2 – Factors considered for the Management Vulnerability indicator

The AHP method was applied first internally for the sanitation parameter, and then for the four parameters considered to integrate this information in one municipal management indicator. The existence of a Municipal Plan for Risk Reduction was considered the most important, followed by programs or actions on risk management. These were both considered more important since their existence shows a clear and direct action and concern on the risk management front by the municipality. The Municipal Plan for Risk Reduction was considered more important, once it provides the organization and guide for the actions and programs for risk reduction.

The Municipal Housing Plan was ranked less important, followed by the Sanitation policy and plan. The sanitation parameter was considered more important if the policy or plan were established by law or regulated, as to whether or not it includes drainage, management and solid waste issues. Between these later two criteria, greater importance was given to the drainage and management component. Policy and plan possess the same relative importance.

2-2.5.2. Environmental vulnerability Indicator ($\boldsymbol{i_{v_{env}}}$)

The environmental vulnerability indicator ($i_{v_{env}}$) brings physical local characteristics related to vulnerability of flood risks. To capture the regions more vulnerable to flooding, this indicator was composed by: a parameter related to the areas prone to flooding and, therefore, closer in height to the rivers and reaches; and by slope, since steep slopes on extreme precipitation events lead to surface runoff at high speeds, creating possible situations of risk. These parameters were crossed with the regions' land uses.

To calculate the height above the nearest drainage the HAND algorithm (Height Above the Nearest Drainage - HAND) was used[32,33] in ENVI 4.7 software (IDL 7.1)[31]. First the Digital Elevation Model from SRTM (2001) with bias correction done for Brazil by EMBRAPA[47] was hydrologically corrected, then, flow direction and drainage were re-calculated, and finally the relative heights to the nearest rivers/reaches was calculated. A flowchart of these steps is shown in Figure 2.3, and the description of the algorithm is presented in Rennó et al.[32]. Slope was calculated based on SRTM and Embrapa DEM in ArcGIS® 9.3 software[29]. One limitation of this methodology is that the HAND algorithm does not take into account the size of the river, amount of streamflow, or its rugosity, only the height above the nearest drainage. Therefore a location one meter in height distance to a small creeck will have the same weight as a location one meter in height distance to a large river.

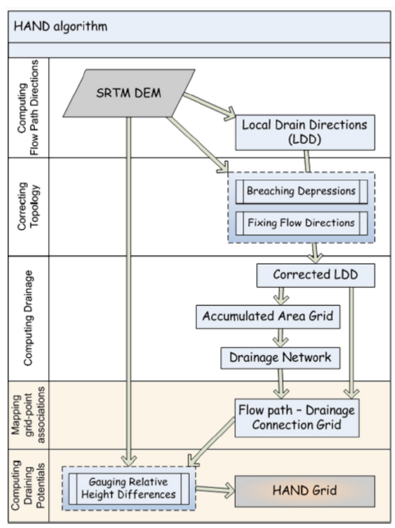

Figure 2-3 - Procedural Steps of the Height Above the Nearest Drainage – HAND[32].

With regard to land uses, two maps were used: one from the PCJ Agency of 2003 for the PCJ watershed and the other of 2010 for the Piracicaba basin only[48]. The more recent map was used for the region where data was available (Piracicaba basin), whereas the 2003 data was used for the rest of the PCJ watershed. The crossing and reclassification of the two maps was done with crosstab tool from Idrisi 32 [30]. Urban areas were ranked with high vulnerability (10) and the other land use classes as low (1), since the major aim of this study was related to human lifes.

The environmental vulnerability index considered the sum of vulnerabilities concerning HAND and slope maps, and then this information was crossed with the land use map: Equation 4. Human risk (which was the study main focus) only depends on the occupancy of a given region. For example, if a flood happens in an area of native vegetation or sugarcane plantation, the risk is much lower than if they occur in urbanized areas. Another index could be created sdressing different weights depending on the crops, based on economic strategic values, but for the purpose of this study this was not done.

$$I_{v_{env}} = Land\ Use * (HAND + Slope) \qquad (4)$$

2-2.5.3. Socioeconomic vulnerability Indicator ($\boldsymbol{i}_{\boldsymbol{v}_{soc}}$)

The socioeconomic vulnerability indicator encompasses indicators related to: habitation/housing ($i_{v_{shab}}$); income ($i_{v_{sinc}}$); literacy ($i_{v_{slit}}$); age ($i_{v_{sage}}$) and the Human Development Index (HDI) ($i_{v_{shdi}}$). This indicator was developed based on previous studies that take socioeconomic factors in consideration[34,41,42,40,44,49,50,51,52,53]. In this study, however, the indicator was created based on the available census database and on the parameters that were considered important for the Brazilian situation.

The housing indicator ($i_{v_{shab}}$) was composed based on the percentage of households considered inadequate or semi-adequate, and on the percentage of non-private owned and settled households. An inadequate household is one without basic sanitation condition: it is not connected to the water supply or sewage networks, nor does it have access to the solid waste collection or septic tanks. Equation 5 shows how this indicator was calculated. The proportion of inadequacy was deemed more important, with inadequate households being more vulnerable (therefore with higher associated weight), then semi-adequate households. The proportion of households not privately owned and fully settled was also considered, but deemed much less important.

$$i_{v_{shab}} = \left[\left(\frac{H_{semi}}{H_{Total}} * 0.6 + \frac{H_{inadequate}}{H_{Total}}\right) * 5 + \frac{H_{not\ settled}}{H_{Total}}\right] /6 \quad (5)$$

In which, H are the households; H_{semi} are the semi-adequate; $H_{inadequate}$ are the inadequate; H_{Total} is the total of households in the Census region; and $H_{not\ settled}$ are the households not privately owned and fully settled.

The income indicator ($i_{v_{sinc}}$) was based on the minimum monthly salary. For 2012 the minimum stipulated salary by law 7.655 of 12/23/2011 was of R$ 622. The income indicator was based on this minimum salary. An income of less than 1/8 of the minimum salary by household is considered within the poverty line. The percentage of households that had no income, less than 1/8 of the minimum salary and households earning up to five minimum salaries were considered in this indicator. The weight given to each can be seen in the equation used for the indicator: Equation 6.

$$i_{v_{sinc}} = \left[(S_{1/8} + S_0) + (S_{1/4} + S_{1/2}) * 0.7 + (S_1 * 0.5) + (S_2 * 0.2) + (S_3 * 0.1) + (S_5 * 0.05)\right] \quad (6)$$

In which, S_n is the percentage of households with income based on the n proportion of the minimum salary. For example: S_0 no income; $S_{1/8}$ income up to 1/8 of the minimum salary; $S_{1/4}$ income from 1/8 to 1/4 of the minimum salary; $S_{1/2}$ income from 1/4 to 1/2 of the minimum salary; S_1 income from 1/2 to 1 minimum salary, etc.

The literacy indicator ($i_{v_{slit}}$) was based on the percentage of residents older than 5 years old that are literate (P_{lit5}) and the percentage of households responsibles that are literate (PR_{lit}). As follows on Equation 7.

$$i_{v_{slit}} = [(1 - P_{lit5}) * 0.5 + (1 - PR_{lit}) * 0.5] \quad (7)$$

The age indicator ($i_{v_{sage}}$) considered as most vulnerable small children (that still cannot walk, up to two years old) and the elderly over 80 years old (with mobility difficulties); secondly the children (considered from 2 until 11 years old by the Brazilian Children's Law 8.069, of 1990) and the elderly from 60 to 80 years old (the World Health Organization consider elderly in developing countries people over 60 years old); and then the teenagers (12 to 18 years old - Brazilian Children's Law), as indicated in Equation 8 below.

$$i_{v_{sage}} = [(P_{<2} + P_{>80}) + (P_{2-11} + P_{60-80}) * 0.6 + (P_{12-18}) * 0.3] \quad (8)$$

$P_{<2}$ is the percentage of children younger than 2 years old; $P_{>80}$ is the percentage of elderly over 80 years old; P_{2-11} is the percentage of people between 2 and 11 years old; P_{60-80} is the percentage of people between 60 to 80 years old; and P_{12-18} is the percentage of teenagers between 12 and 18.

These four indicators were normalized based on a linear regression. Then, they were averaged together to compose the vulnerability socioeconomic indicator. But, since we believed that the most determining factors were income, age and housing, and that literacy was a less ruling factor, $i_{v_{slit}}$ weighs half of the other three ($i_{v_{shab}}, i_{v_{sinc}}, i_{v_{sage}}$) for a weighted average.

However, since about 5% of census sectors in the study area had no data, we proposed to also use the Human Development Index (HDI), which is composed of information on: income, education and health[54] and regards the municipal level. Therefore, an indicator based on HDI ($i_{v_{shdi}}$) was established to be on the same scale as the socioeconomic composed index; for the census sectors without data, only the municipal $i_{v_{shdi}}$ was used as the $i_{v_{soc}}$; for the sectors with data, a weighted average was done, with weight 2 for the socioeconomic census based index and 1 for the $i_{v_{shdi}}$, Equation 9.

$$i_{v_{soc}} = \begin{cases} i_{v_{shdi}}, & if\ no\ available\ census\ data \\ \left[\left(\frac{i_{v_{sage}} + \left(i_{v_{slit}} * 0.5\right) + i_{v_{sinc}} + i_{v_{shab}}}{3.5}\right) * 2 + i_{v_{shdi}}\right] / 3, & if\ census\ data\ is\ available \end{cases} \quad (9)$$

This decision amounts to the fact that the census data are local, more recent and have better spatial resolution. The weighing of the HDI indicator was also required because of the sectors without data and because this criteria includes a health component (for example) that was not taken into consideration before.

2-3. Results and Discussion

The results for each component of the risk index will be presented first. Initially, all the results for the Hazard Index; secondly, the Exposure Index and Vulnerability Index (management, environmental and socioeconomic indicators); finally, the composed risk index.

2-3.1. Hazard Index (I_{haz})

In Figure 2-4, one example of the sigmoidal function (Eq. 2), used to normalize the parameters for the maximum precipitation over a day, is presented. Table 2.2 presents the weighting of the parameters and levels of importance for the AHP method; a CR of 0.05 was obtained.

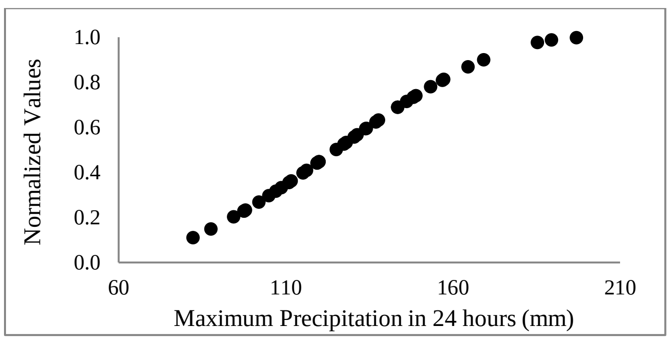

Figure 2-4 - Normalization through a sigmoidal function for maximum precipitation over a day

Table 2-2 - AHP Method applied for the Hazard Index' parameters

	Maximum Precipitation (in a day)	**Averages of Annual Maximum Precipitation (in a day)**	**Maximum Precipitation (in 3 days)**	**Annual Average of days with precipitation in between 25-50mm**	**Annual Average of days with precipitation greater than 50mm**
Maximum Precipitation (in a day)	1.00	3.00	5.00	9.00	6.00
Averages of Annual Maximum Precipitation (in a day)	0.33	1.00	2.00	7.00	5.00
Maximum Precipitation (in 3 days)	0.20	0.50	1.00	7.00	2.00

Annual Average of days with precipitation in between 25-50mm	0.11	0.14	0.14	1.00	0.33
Annual Average of days with precipitation greater than 50mm	0.17	0.20	0.50	3.00	1.00

Figure 2-5 to Figure 2-9 show the maps of the parameters used to create the hazard index. Their results can be seen by interpolated Thyessen Polygons. There is no clear pattern between all the results related to the hazard front. From Figure 2-5, with the average of annual maximum precipitation over a day, one can see that the west side, a region on the central-east and the southeast corner, have the higher averages of intense precipitations on a day, with averages from 80 to more than 120 mm. Although only four gauge stations had average annual maximum rainfall higher than 100 mm/day.

In relation to the maximum precipitation values over a day in the period studied (Figure 2-6), the behavior is different, but some tendencies are maintained. High values on the southeast corner (upstream of the watershed) and in the central to east region, as well as a few polygons related to stations on the west of the watershed. The smallest value was 82 mm and the highest 202mm. Only in 15% of the polygons the most intense precipitation in a day was less than 100 mm, the majority (63%) were between 100 and 150 mm, and 22% larger than 150 mm/day.

For the maximum precipitation over 3 days (Figure 2-7), the trend looks different, with higher values on the west and northeast regions. The observed range is 133 to 283 mm over 3 days. In relation to the frequency of medium intensity rainfalls (between 25-50mm/day, Figure 2-8) and higher intensity (above 50mm/day, Figure 2-9) the patterns seem to differ. For the smaller intensity precipitations the greater average of number of days in the year was to the east portion of the watershed (areas with more forest cover), whereas the areas with more days with higher intensity rainfalls are located to center and to west of the watershed.

The spatialized hazard index (I_{haz}) is shown in Figure 2-10. It combines all the information of the previous parameters (Figure 2-5 - Figure 2-9), as described in the methodology. The index scale goes from 1 to 10, being 1 the lowest hazard and 10 the highest for the watershed.

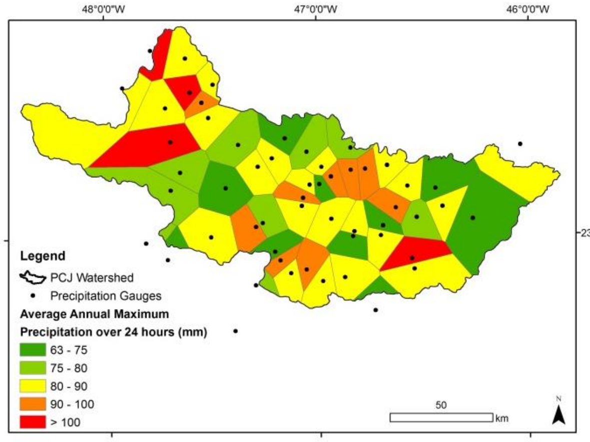

Figure 2-5 - Annual Averages of Maximum precipitation over a day

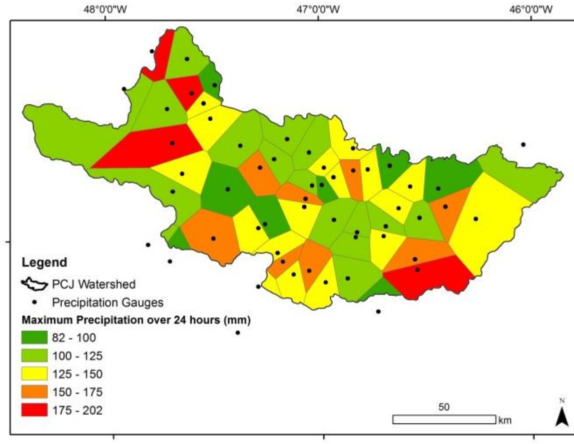

Figure 2-6 - Maximum precipitation over a day

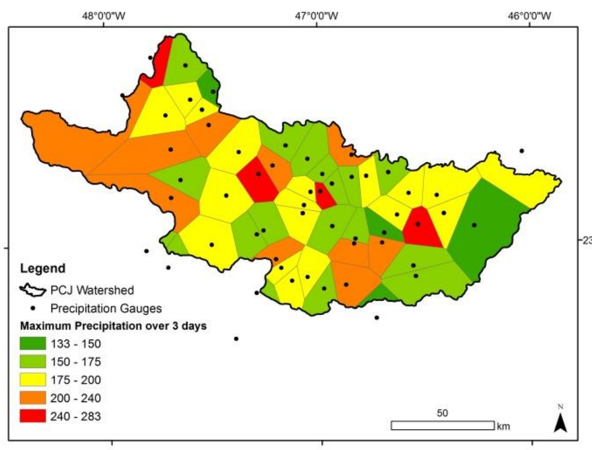

Figure 2-7 - Maximum precipitation over 3 days

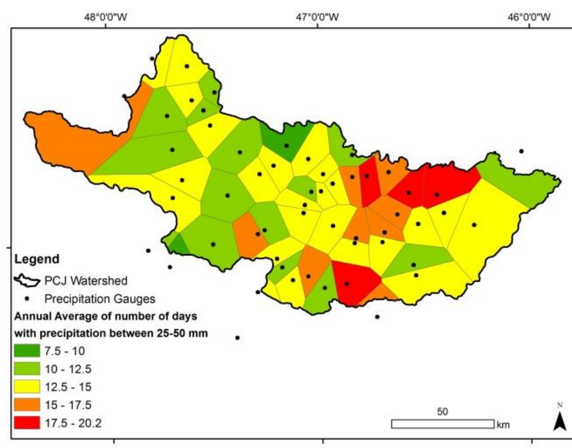

Figure 2-8 - Annual Average of number of days with precipitation between 25-50mm

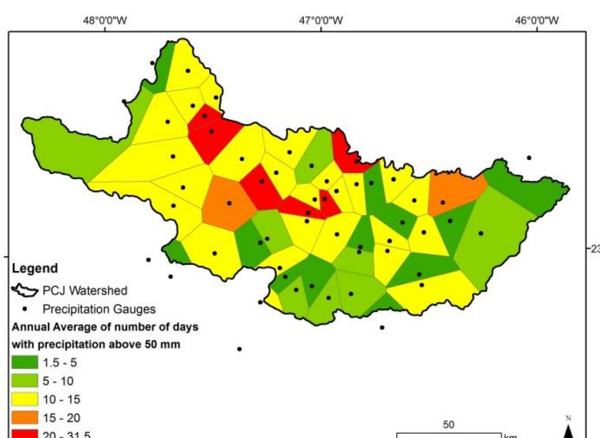

Figure 2-9 - Annual Average of number of days with precipitation above 50mm

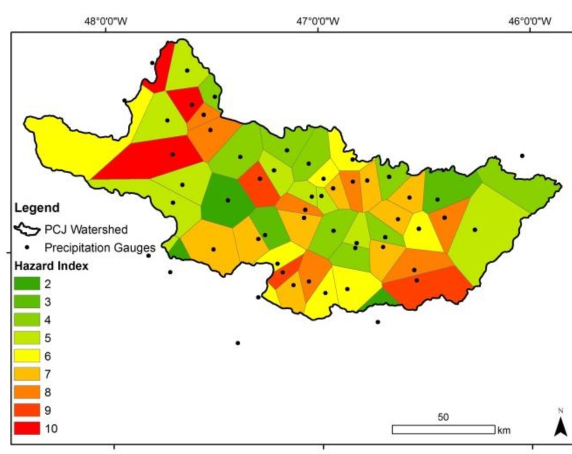

Figure 2-10 - Spatialized Hazard Index

2-3.2. Exposure Index (I_{exp})

The exposure index spatialized for the PCJ watershed is shown on Figure 2-11. This map is related to the demography of the census regions; therefore, areas with low population concentrations (rural areas) have the lowest index values, while areas with higher population concentration (cities) have higher exposure, and the denser neighborhoods have the highest index.

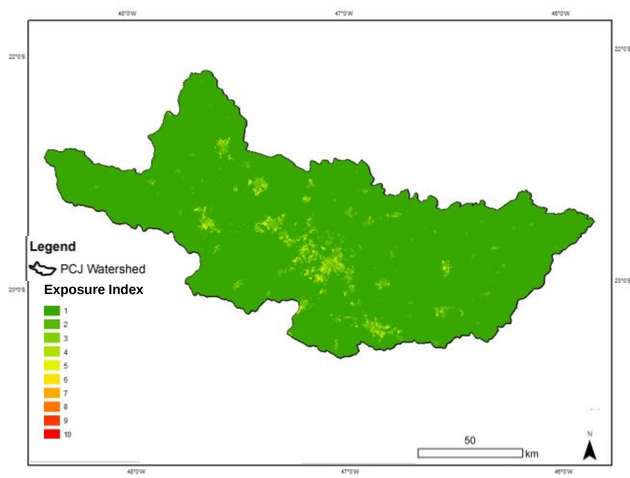

Figure 2-11 - –Exposure Index (I_{exp})

2-3.3. Vulnerability Index (I_{vul})

In the following items, the results for the vulnerability indicators (related to management, environment and socioeconomic) that compose the vulnerability index are presented.

2-3.3.1. Management Vulnerability Indicator ($i_{v_{mgt}}$)

Table 2-3 and Table 2-4 bring forward the weighting used to compose the management vulnerability indicator, elaborated with the AHP method. The first elements to be done were the weights within the sanitation policy and plan (Table 2-3); their average composed the sanitation component. Then, the relative importance between the four components was measured (Table 2-4); the CR obtained was 0.027. The management vulnerability indicator was calculated based on a weighted average of these four parameters, according to the given weights.

Table 2-3 - AHP Method for the sanitation considered aspects

	If it is regulated or implemented as law	**If it covers waste management**	**If it covers drainage and management**
If it is regulated or implemented as law	1	2	2
If it covers waste management	0. 5	1	0.5
If it covers drainage and management	0. 5	2	1

Table 2-4 – AHP Method for the management vulnerability index ($i_{v_{mgt}}$)

	Existence of a municipal plan for housing	**Existence of a municipal plan for risk reduction**	**Existence of programs and actions on risk management**	**Sanitation plan and policy aspects**
Existence of a municipal plan for housing	1	0.2	0.33	1
Existence of a municipal plan for risk reduction	5	1	2	5
Existence of programs and actions on risk management	3	0.5	1	3
Sanitation plan and policy aspects	1	0.2	0.33	1

The parameters that compose the $i_{v_{mgt}}$ are presented in Figure 2-12 to Figure 2-15. They are the municipal plan for risk reduction, if it exists, or not, or if it is under elaboration (Figure 2-12); the existence of programs and actions on risk management (Figure 2-13); the existence of a municipal plan for housing (Figure 2-14); and the sanitation component (Figure 2-15), that is further composed by the existence of a sanitation policy and plan, if they are regulated (plan) or instituted as law (for the policy) and if they contain the areas of drainage and waste management.

Being 1 the most vulnerable (absence of plan or risk management actions or programs); 0.7 in the case of preparation of the plan or policy; and 0 being less vulnerable: in this case with a municipal strategy (plans, programs or actions) in place. In Figure 2-16 the Management Vulnerability Indicator ($i_{v_{mgt}}$) is presented.

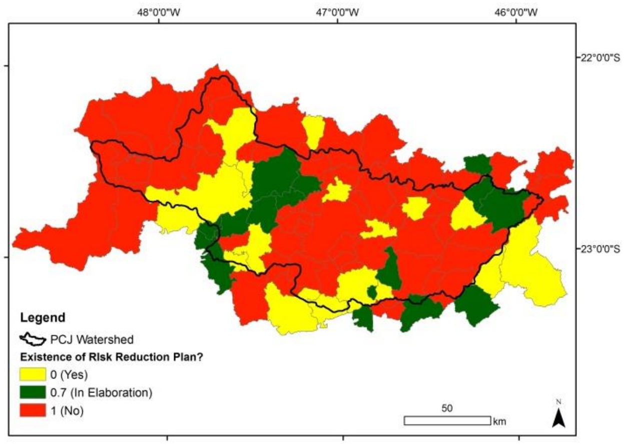

Figure 2-12 - Existence of Risk Reduction Municipal Plan

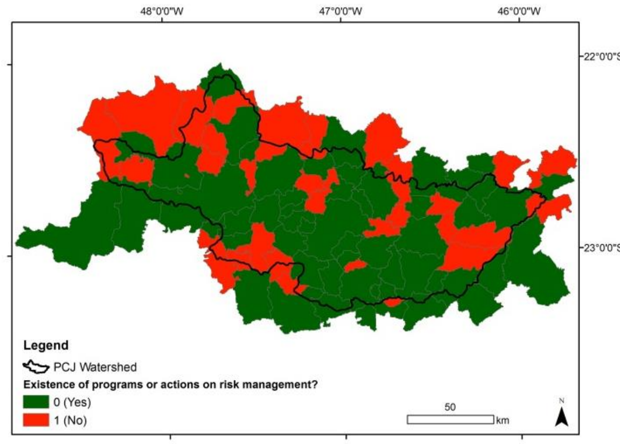

Figure 2-13 - Existence of Risk management programs and actions

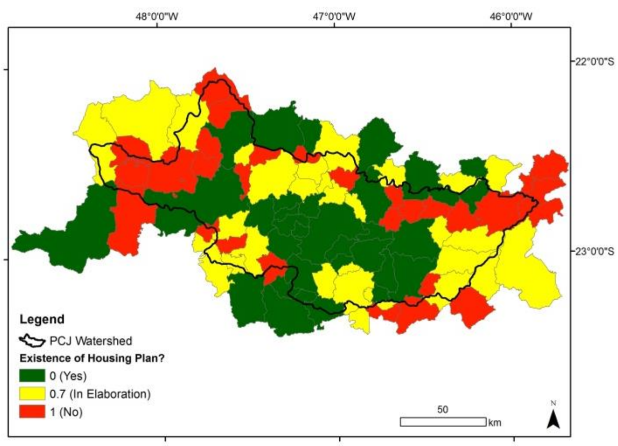

Figure 2-14 - Existence of a Housing Municipal Plan

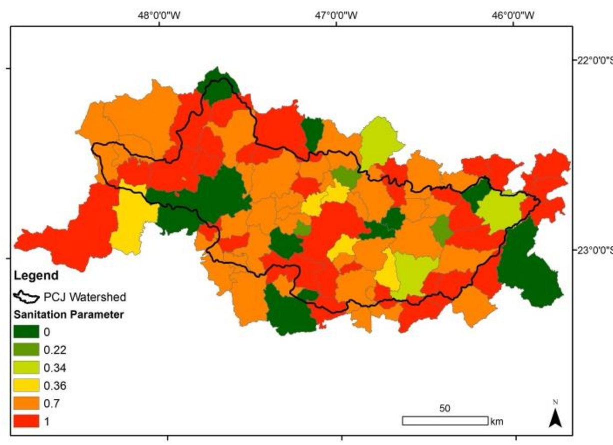

Figure 2-15 - Sanitation Parameter

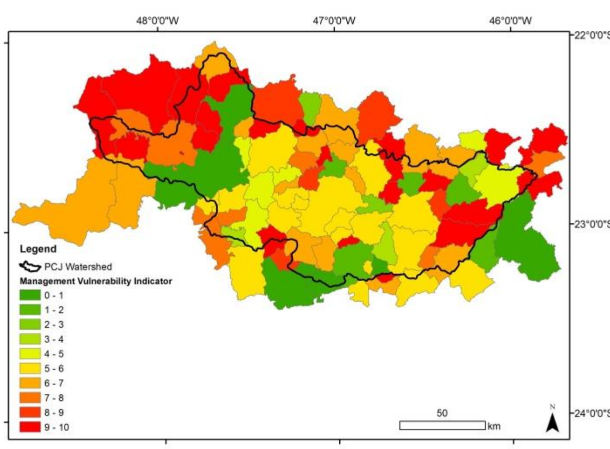

Figure 2-16 - Management Vulnerability Indicator ($i_{v_{mgt}}$)

From the 91 municipalities in the watershed, 66% did not have a municipal plan for risk reduction, 16% were still preparing the plan and only 18% had a plan in place (Figure 2-12). More than 61% of the municipalities claimed they had programs and actions on risk management (Figure 2-13), even though many were not guided through or followed a plan (since only 18% had a risk reduction plan). In relation to the municipal housing plan (Figure 2-14), the figure was about even, with approximately 1/3 of the municipalities having a plan, 1/3 elaborating one, and 1/3 not having it. From the sanitation indicator, which related to a series of information (Figure 2-15), only 9 municipalities (~10%) had met all the criteria, 46 had some of the criteria met, and 36 (~40%) had none of the criteria met (with no sanitation plan nor policy).

The Management Vulnerability Indicator ($i_{v_{mgt}}$) (Figure 2-16) had a diverse range of values, showing the different levels of management organization of the municipalities (related to risk reduction and the census parameters that were available). It is, although, very concerning that many municipalities had high ranked vulnerabilities related to management (with orange and red colors, with values larger than 7), showing the lack of importance and prepare even to establish the basic governmental guidelines on risk reduction and related management.

2-3.3.2. Environmental Vulnerability Indicator ($i_{v_{env}}$)

Figure 2-17 to Figure 2-19 show the components of the environmental vulnerability indicators, relating to land use (Figure 2-17), to the height above the nearest drainage (HAND) (Figure 2-18), and to the slope (Figure 2-19). The compound environmental vulnerability indicator (based on Figure 2-17 to Figure 2-19) for the PCJ watershed is shown in Figure 2-20. From the reclassified land use map (Figure 2-17), one can see that the watershed is mainly rural, with a bigger concentration of cities in the center region of the watershed. The HAND indicator was also reclassified (normalized) and, as it can be seen of Figure 2-18, the regions with smaller height distance to the rivers have higher vulnerability. From the slope maps we can clearly see the upperstream regions of the watershed. The higher vulnerability was attributed to higher slope. The combination of these three parameters compose the environment vulnerability indicator (Figure 2-20), which shows that the higher environment vulnerable areas are urban areas close to the drainage or with high slopes.

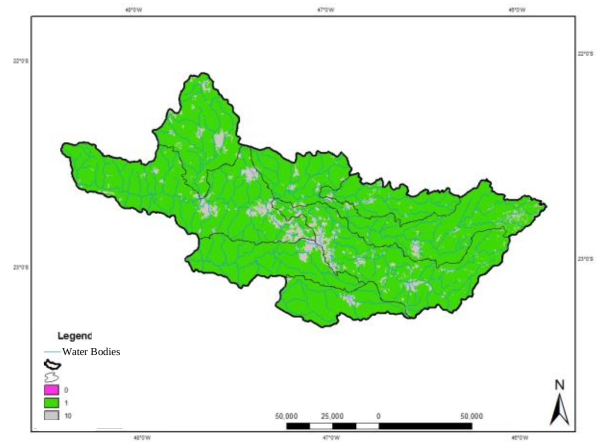

Figure 2-17 - Vulnerability Indicator related to land use

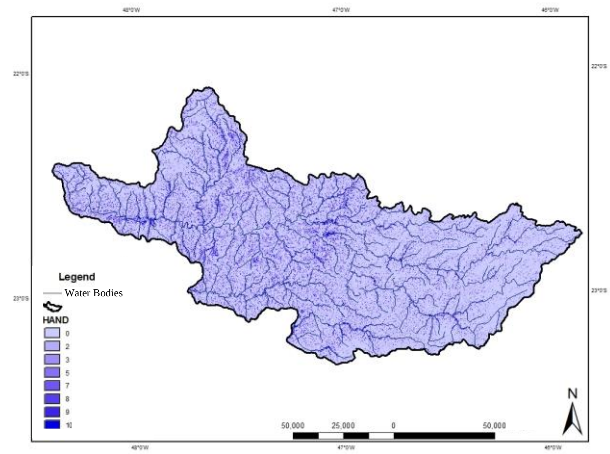

Figure 2-18 - – Vulnerability Indicator related to HAND

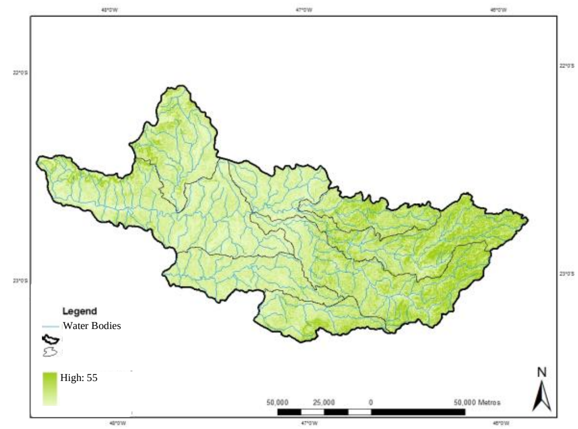

Figure 2-19 - Slope

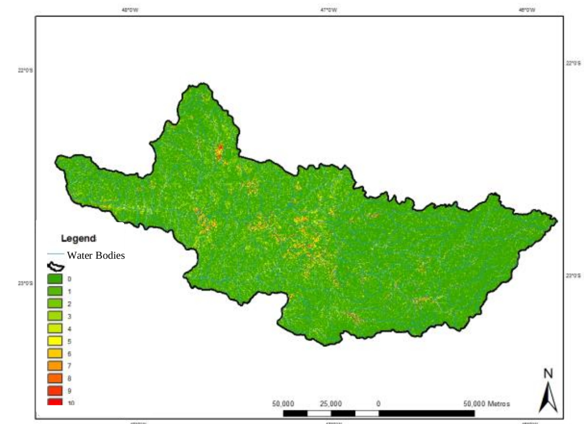

Figure 2-20 - Environmental Vulnerability Indicator

2-3.2.3. Socioeconomic Vulnerability Indicator ($\boldsymbol{i_{v_{soc}}}$)

Figure 2-21 to Figure 2-25 show the five indicators related to: income ($i_{v_{sinc}}$); housing/habitation ($i_{v_{shab}}$); literacy ($i_{v_{slit}}$); age ($i_{v_{sage}}$); and the Human Development Index (HDI). These five indicators compose the socioeconomic vulnerability indicator ($i_{v_{soc}}$) (Figure 2-26). The indicators: $i_{v_{shab}}$, $i_{v_{sinc}}$, $i_{v_{slit}}$ and $i_{v_{sage}}$ are related to the Census regions parameters, while the HDI is a United Nations information[54], that regards the municipality level. One can see that higher vulnerability related to income and literacy (Figure 2-21 and Figure 2-23) happens mainly in rural areas.

The values of the HDI were presented (Figure 2-25), instead of the indicator (not inverted, nor normalized), since many can relate to it. One can see that many of the lower HDI values (worse) are on the upstream areas of the watershed, but also in a strip in the middle and to the west. The highest (better, smaller vulnerability) HDI values are in the following municipalities: Águas de São Pedro, Campinas, Jundiaí, Laranjal Paulista, Leme, Lençóis Paulista. The socioeconomic vulnerability indicator (Figure 2-26) is more pronounced (with greater vulnerability) for the regions on the edge of the watershed and more rural areas.

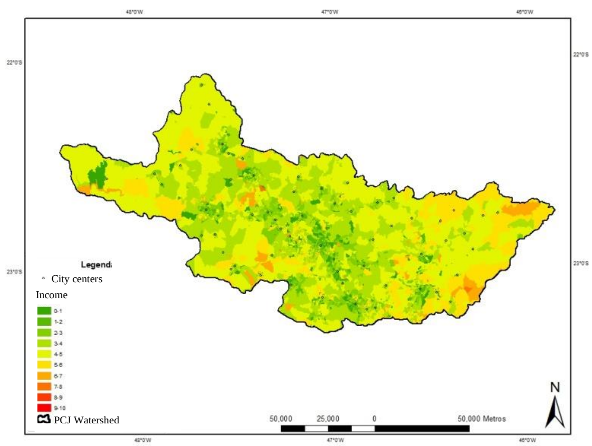

Figure 2-21 - Income Socio-economic Vulnerability Indicator

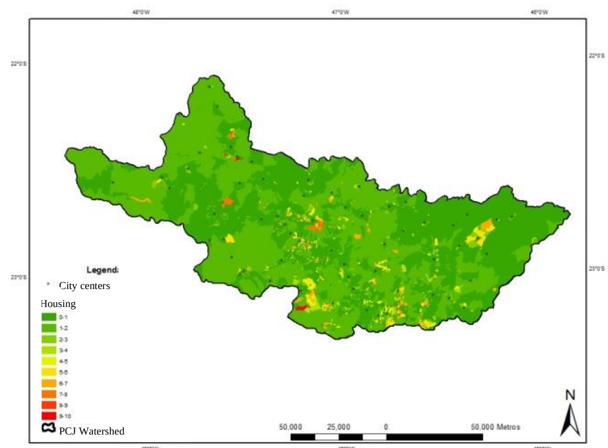

Figure 2-22 - Housing Socio-economic Vulnerability Indicator

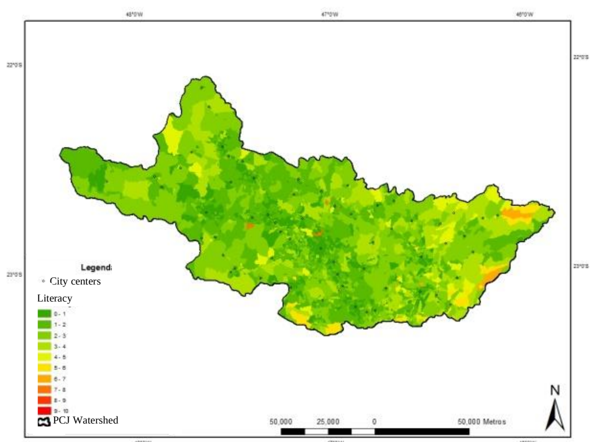

Figure 2-23 - Literacy Socio-economic Vulnerability Indicator

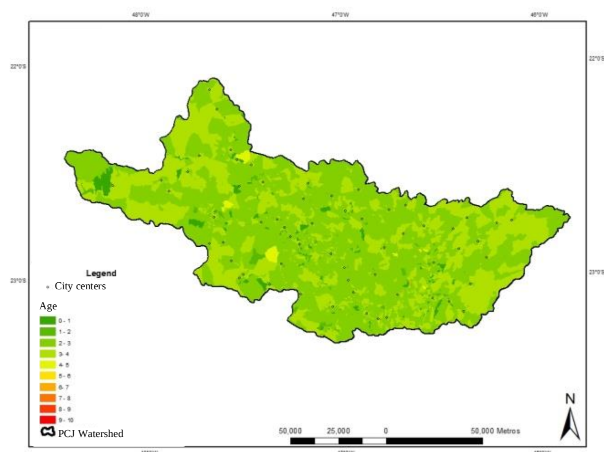

Figure 2-24 - Age Socio-economic Vulnerability Indicator

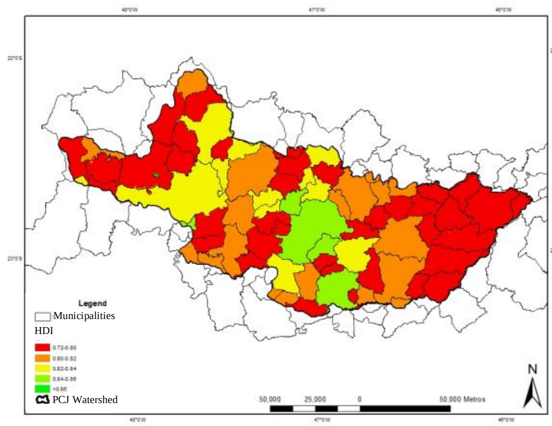

Figure 2-25 - HDI

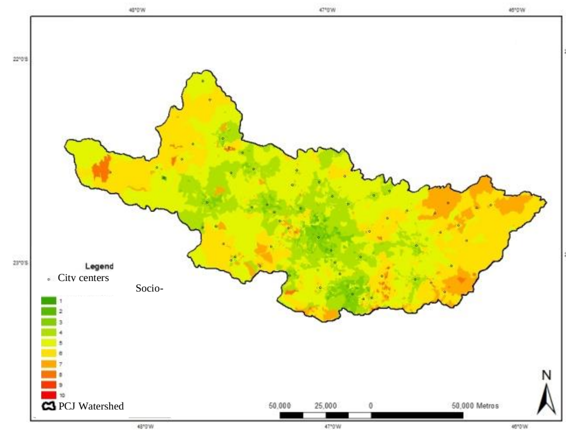

Figure 2-26 - Socio-economic Vulnerability Indicator

2-3.4. Risk Index (I_{risk})

The final results of the flooding risk index are spatially presented for the PCJ watershed (Figure 2-27). The values were aggregated by municipalities through a weighted average based on the area (Figure 2-28). The task of developing risk indices and assessing risk is not limited to the determination of areas with greater probability of having flooding issues, it is also important to combine all different qualitatively and quantitatively components related to risk, and provide their values and distributions. We sought to identify the related aspects to flooding risks, according to the Brazilian reality, relying on available data regarding relevant parameters. The aim was to conduct a proper assessment of flooding risks, engaging different and important concepts on this matter. Even though they may be unable to capture the exact situation of a given locality, especially concerning the occurrence of a localized event, the presentation of a spatialized index is important and can be easily understood and visualized.

It is also important to pinpoint that some decisions had to be made in order to compose of this spatialized flooding risk index. The weighting and parameters could also be done with the input of different stakeholders, to take into account the different sectors and people from society. The mapping of all different parameters and indicators of vulnerability (environmental, management, socio-economic and combined); exposure; and hazard; as well as the flooding risk index, can be used as important tools to plan and to know where and what to improve, as well as which regions and sectors to prioritize. They are crucial for the Federal and State governments to decide how to prioritize resources and to act in determined fronts and regions.

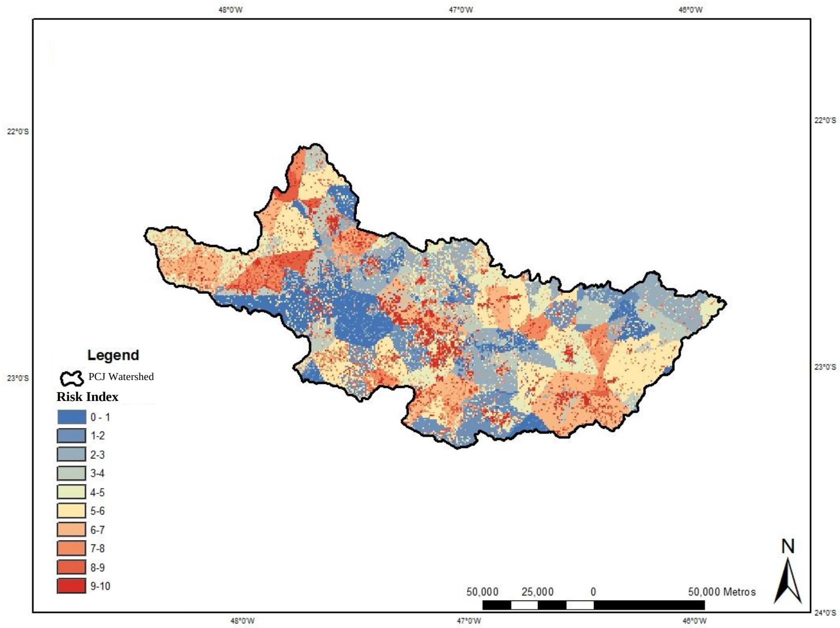

Figure 2-27 - Risk Index for PCJ Watershed

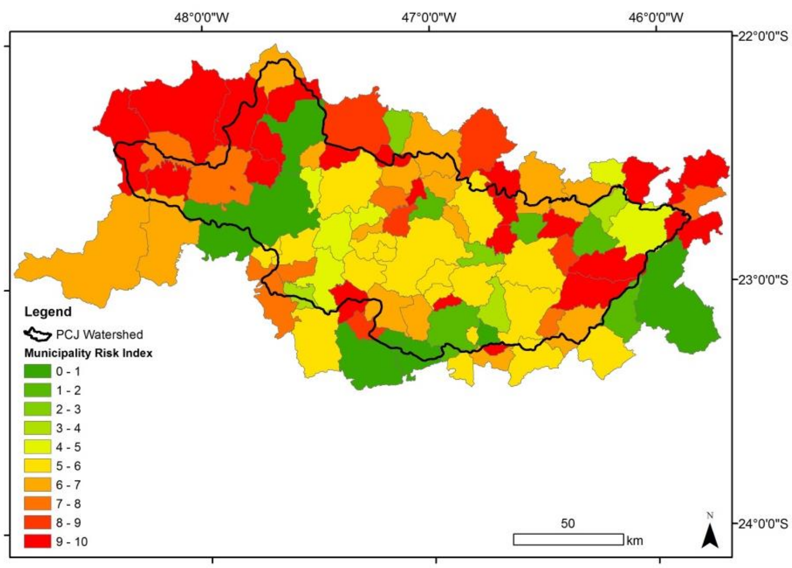

Figure 2-28 - Municipality Risk Index

From Figure 2-27, with the spatialized flooding risk index, one can clearly see the effect of the hazard index, through the Thyessen polygons; the exposure index, through the more populated areas; but also the less predictable aspects of the vulnerability index. Figure 2-28 shows the aggregated values by municipality in a weighted average by area. It is important to stress that this way of aggregation may hide high or smooth internal risk dynamics. Nevertheless, this map was created to provide the big picture, since flooding problems are local and the administrative power is in the municipality level.

2.4. Conclusions

A flooding risk index and its components (that influence risk) were developed and presented. These mappings can be important tools for planning, in neighborhood, municipal, state and federal levels, assisting watershed committees to identify deficiencies, to adapt in the face of floods, to reduce the vulnerability and become more resilient to extreme events. These indices and indicators can, therefore, be very important tools, but they must be used carefully, since they contain limitations and uncertainties, as the ones regarding the resolution and quality of the data used, limitations of methodology (as for example the HAND method), the combination of qualitative and quantitative parameters, as well as the weighting of the parameters used. We also tried to validate these indices with data from flood occurrances from the civil defense, the problem was that the data had an enormous quantity of uncertainties, and was very specific of the city and of the civil defense organization and person in charge, therefore the comparison was difficult. We advise future studies to validate this methodology (at least between neighborhoods in a city) comparing the observed data of previous flood occurrances, as also data from midia releases for example.

These maps can be tools to give indications of where action must be taken and to aid in decision making and planning. It should not be used as a forecasting tool of human losses, for example. This established methodology can be applied for the entire São Paulo state, or for the entire country, since it takes into account important internal parameters, already available at national scale, allowing the identification of critical regions and quantification of risks related to flooding.

2.5. References

1 - UNISDR (United Nations – International Strategy for Disaster Reduction) (2011). Global Assessment Report on Disaster Risk Reduction 2011 – Revealing Risk, Redefining Development. Suiça, 2011.

2 - MUNICH RE. Munich Re Topics Geo 2005. Munich Re Group, 2006, 56 p.

3 - MUNICH RE. Munich Re Topics Geo 2010. Munich Re Group, 2011, 58 p.

4 - International Federation of Red Cross and Red Crescent Societies (IFRC). World Disasters Report- Focus on Recovery. IFRC, 2001. Genebra, Suiça, 222p.

5 - Mendiondo EM. Reducing vulnerability to water-related disasters in urban areas of the humid tropics; in: Integrated Urban Water Management: Humid Tropics. Org. Parkinson, J. N., Goldefum, J. A e Tucci, C.E.M., UNESCO. vol. 6, Chapter 6, 2010.

6 - Atlas Brasileiro de Desastres Naturais, 2011

7 - Dixon B; Earls J. Effects of urbanization on streamflow using SWAT with real and simulated meteorological data. Applied Geography, 2012, 35, 174-190.

8 - Bressiani D; Brandão JLB; Mendiondo EM; Sivapalan M. Hidrologia Urbana no Brasil e nos Estados Unidos: Estudo de Caso das Cidades de São Carlos, SP, Brasil e Chicago, Illinois, EUA, In: X Simp. Bras. Rec. Hídricos do Nordeste, Fortaleza, CE, Anais CD Room, 16-19 Nov, 2010.

9 - Dutta D, Herath S, Musiake K. Flood inundation simulation in a river basin using a physically based distributed hydrologic model. Hydrological Processes. 2000. 14(3): 497-519.

10 - Dolcine L, Andrieu H, Sempre-Torres D, Creutin D. Flash flood forecasting with coupled precipitation model in mountainous Mediterranean basin. Journal of Hydrologic Engineering. 2001. 6 (1): 1–10.

11 - Knebl MR, Yang ZL, Hutchison K, Maidment DR. Regional Scale flood modeling using NEXRAD rainfall, GIS, and HEC-HMS/RAS: a case study for the San Antonio River Basin Summer 2002 storm event. Journal of Environmental Management. 2005. 75: 325-336.

12 - Tucci CEM. Inundações Urbanas na América do Sul. Capítulo 6: Brasil. Organizado por C. E. M. Tucci e Juan C. Bertoni. Porto Alegr: ABRH, 2003

13 - Canholi AP. O Plano Diretor de Macrodrenagem da bacia do Alto Tietê. São Paulo. 2002

14 - Intergovernmental Panel On Climate Change (IPCC). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. New York: IPCC, 2012. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. 582 p, 2012.

15 – DKKV (German Committee for Disaster Reduction) e UNISDR(United Nations – International Strategy for Disaster Reduction). Emerging challenges for early warning systems in context of climate change and urbanization. Humanitarian Development Network, CH 1296 Coppet, Suiça, Setembro 2010.

16 - UN-Water. Climate Change Adaptation: the pivotal role of water. Policy Break. p.1-18, 2010.

17 - Price RK, Vojinovic Z. Urban flood disaster management. Urban Water Journal. 2008. 5(3): 259-276.

18 - UNISDR (United Nations International Strategy for Disaster Reduction). Sendai framework for disaster risk reduction 2015–2030, 2015. Geneva: UNISDR.

19 - Kron W. Flood insurance: from clients to global financial markets. Flood Risk Management, 2009, 2, p.68-75.

20 - Godschalk D. Urban hazard mitigation: Creating Resilient Cities. Natural Hazard Review, ASCE, 2003, 4(3), p. 136-143.

21 - Sherbinin A; Schiller A; Pulsipher A. The vulnerability of global cities to climate hazards. Environment Urbanization, IIED, 2007, 19(1), p.39-64.

22 - Mukheibir P; Ziervogel G. Developing a Municipal Adaptation Plan (MAP) for climate change: the city of Cape Town. Environment Urbanization, IIED, 2007, 19(1), p.143-158.

23 - Huq S; Kovats S; Reid H; Satterthwaite, D. Editorial: Reducing risks to cities from disasters and climate change. Environment Urbanization, IIED, 2007, 19(1), p.3-15.

24 - Alam M, Rabbani G. Vulnerabilities and responses to climate change for Dhaka. Environment Urbanization, IIED. 2007. 19(1):81-97.

25- Secretaria Do Meio Ambiente/ Coordenadoria De Recursos Hídricos (SMA/CRH). Situação dos Recursos Hídricos no Estado de São Paulo: Ano base 2007. São Paulo: SMA, 2009. 147 p.

26 - Instituto Brasileiro de Geografia e Estatística-IBGE (2000). *Sedes municipais (IBGE - 2000).* Brasil, 2000.

27 - Cardona OD. Indicators for Disaster Risk and Risk Management. Program for Latin America and the Caribbean: Summary Report, Manizales, Columbia: Instituto de Estudios Ambientales, Universidade Nacional de Columbia, 2005.

28 - Peduzzi P; Dao H; Herold C; Mouton F. Assessing global exposure and vulnerability towards natural hazards: the Disaster Risk Index. Natural Hazards and Earth System Sciences, 2009, 9, 1149-1159.

29 - ESRI. ArcGIS® 9.3 Enterprise Deployment - An ESRI ® Technical Paper. July, 2008. Redlands, CA, USA.

30 - Eastman JR. Idrisi32: Idrisi for Workstations, Release 2 (Worcester, MA: Clark University) 2001.

31- ITT Visual Information Solutions. ENVI Reference Guide: ENVI Version 4.7 (IDL 7.1). August, 2009. Technical Paper 20REF47DOC.

32 - Rennó CD; Nobre AD; Cuartas LA; Soares JV; Hodnett MG; Tomasella J; Waterloo MJ. HAND, a new terrain descriptor using SRTM-DEM: Mapping terra-firme rainforest environments in Amazonia, Remote Sensing of Environment, 2008, 112(9), p. 3469-3481, ISSN 0034-4257, 10.1016/j.rse.2008.03.018. (http://www.sciencedirect.com/science/article/pii/S003442570800120X)

33 - Nobre AD, Cuartas LA, Hodnett M, Rennó CD, Rodrigues G, Silveira A, Waterloo M, Saleska S, Height Above the Nearest Drainage – a hydrologically relevant new terrain model, Journal of Hydrology, Volume 404, Issues 1–2, 29 June 2011, Pages 13-29, ISSN 0022-1694, 10.1016/j.jhydrol.2011.03.051.

34 - Jiang W, Deng L, Chen L, Wu J, Li J. Risk assessment and validation of flood disaster based on fuzzy mathematics, Progress in Natural Science, 2009, 19(10), p. 1419-1425, ISSN 1002-0071, 10.1016/j.pnsc.2008.12.010. (http://www.sciencedirect.com/ science/article/pii/S1002007109002081)

35 - Rodrigues DBB; Rodrigues JP; Silva LF; Oliveira PTS. Multi-criteria analysis in the strategic environmental assessment of the sugar and alcohol sector. Acta Scientiarum. Technology (Online), 2012, 34, p. 1-10.

36 - Saaty TL. A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology. 1977. 15(3): 234-281.

37 - Saaty TL. The analytical hierarchy process: planning, priority setting, resource allocation. New York: McGraw-Hill. 1980.

38 - Thiessen, A. H. Precipitation averages for large areas. Mon. Wea. Rev., 1911, 39, 1082–1089. doi: 10.1175/1520-0493(1911)39<1082b:PAFLA>2.0.CO;2

39 - Instituto Brasileiro de Geografia e Estatística-IBGE (2011). Base de informações do Censo Demográfico 2010: Resultados do Universo por setor censitário. Brasil, 2011.

40 - Peduzzi P, Dao H, Herold C, Mouton F. Assessing global exposure and vulnerability towards natural hazards: the Disaster Risk Index. Natural Hazards and Earth System Sciences. 2009. 9: 1149-1159.

41 - Esnard A, Sapat A, Mitsova D. An index of relative displacement risk to hurricanes. Natural Hazards. 2011, 59(2) p. 833-859.

42 - Li Q, Zhou J, Liu D, Jiang X. Research on flood risk analysis and evaluation method based on variable fuzzy sets and information diffusion, Safety Science, 2012, 50(5) p. 1275-1283, ISSN 0925-7535, 10.1016/ j.ssci.2012.01.007. (http://www.sciencedirect.com/science/article/pii/S092575351 2000100).

43 - Adhikari P, Hong Y, Douglas KR, Kirschbaum DB, Gourley J, Adler R, Brakenridge GR. A digitized global flood inventory (1998–2008): compilation and preliminary results. 2010. Natural Hazards. 55(2): 405-422

44 - Islam MS, Swapan MSH, Haque SM, Disaster risk index: How far should it take account of local attributes? International Journal of Disaster Risk Reduction, Available online 12 November 2012, ISSN 2212-4209, 10.1016/j.ijdrr.2012.10.001. (http://www.sciencedirect.com/science/article/pii/ S2212420912000313)

45 - ITT Visual Information Solutions. ENVI Reference Guide: ENVI Version 4.7 (IDL 7.1). August, 2009. Technical Paper 20REF47DOC.

46 - Farr TG, et al. The Shuttle Radar Topography Mission. Rev. Geophys. 2007. 45, RG2004, doi:10.1029/2005RG000183.

47 - Miranda EE (Coord.). Brasil em Relevo. Campinas: Embrapa Monitoramento por Satélite, 2005. Available at: <http://www.relevobr.cnpm.embrapa.br>. Acessed on: Oct, 2012.

48 – Laurentis G; Pimentel I; Bressiani DA; Mendiondo EM. Aplicabilidade de modelos de transferência de riscos hidrológicos como estratégia da adaptação a eventos extremos.. In: XIX Simpósio Brasileiro de Recursos Hídricos, 2011, Maceió, AL. Anais do XIX Simpósio Brasileiro de Recursos Hídricos, 2011.

49 - Carvalho MD, Barros RPD, Franco S. Índice de Desenvolvimento da Família (IDF), 2003, p. 241-265. In: Acosta AR, Vitale MAF (orgs.). Família: redes, laços e políticas. Instituto de Estudos Especiais/PUC. São Paulo.

50 - Confalonieri UEC, Marinho DP, Rodriguez RER, Public Health Vulnerability to Climate Change in Brazil. Climate Research, 2009, 40, p. 175-186.

51 - Consórcio Imagem - WWF Brasil, 2004. Mapa de vulnerabilidade ambiental do Estado de Goiás, Brasil. Relatório Técnico. 2004.

52 - Haselbalg C. Pobreza no Brasil no final do século XX. Origens e destinos: desigualdades sociais ao longo da vida. In: Haselbalg C, Silva NDV (orgs.). Topbooks. 2003, Rio de Janeiro.

53 - SEA/RJ Fiocruz, Secretaria do Ambiente do Rio de Janeiro e FIOCRUZ, Relatório 4: Mapa de Vulnerabilidade da População do Estado do Rio de Janeiro aos Impactos das Mudanças Climáticas nas Áreas Social, Saúde e Meio Ambiente, 2011.

54 - UNDP - United Nations Development Programme. HDR – Human Development Report (2000). United Nations Development Programme (UNDP); Oxford University Press. 2000. ISBN 0-19-521678-4.

55 - Burton I, Kates RW, White GF: The environment as hazard, Oxford University Press, New York, 240 pp., 1978.

3. *A review of Soil and Water Assessment Tool (SWAT) applications in Brazil: challenges and prospects*

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Abstract

The geographical extent of Brazil exceeds 8.5 million km^2 and encompasses a complex mix of biomes and other environmental conditions. Multiple decision support tools are needed to help support management of these diverse Brazilian natural resources including ecohydrological models. The use of the Soil and Water Assessment Tool (SWAT) ecohydrological watershed-scale model in Brazil has increased greatly during the past decade. Well over 100 SWAT studies were identified in this review which have been published during 1999 to 2015 in Brazilian and international journals, conference proceedings, and as theses or dissertations, many of which are written in Portuguese. The majority of these studies (102 total) are reviewed here as part of an extensive survey covering the 1999 to 2013 time period. Temporal and spatial distributions, a summary of hydrologic calibration and validation results and a synopsis of the types of applications that were performed are reported for the surveyed studies. A smaller subset of recent Brazilian studies published in English between 2012 and 2015 in scientific journals are also reviewed, with emphasis on hydrologic and sediment transport testing results as well as scenario applications that were performed. The majority of the surveyed SWAT studies was performed for watersheds located in the South and Southeast regions of Brazil (67%) and was conducted in the context of academic research. Nearly 50% of the surveyed studies reported only hydrologic results. Similar trends were found for the subset of more recent English publications. Limited studies have been reported that describe applications of SWAT in Brazil by private firms or

government agencies; this review indicates that the potential exists for increased numbers of such studies in the future. However, there is evidence that a lack of accessibility to adequate quality input data is a possible hindrance to the more general use of SWAT for watershed applications in Brazil.

Keywords: SWAT, Brazil, review paper, mapping applications.

3-1. Introduction

The Brazilian National Water Resources Policy (NWRP)[1,2] was approved in 1997, with the intent of meeting the objectives and principles of Integrated Water Resources Management (IWRM)[3]. The NWRP is further designed to align with the first and fourth "Dublin principles"[4], which include the following objectives: (1) rational and sustainable use of the water resources, to ensure that adequate supplies of quality water are maintained for current and future uses, and (2) considering water resources as a finite public good which are limited in nature and endowed with economic value. The Dublin principles were an attempt to concisely state the main issues and thrust of water management; they were formulated in an international consultative process that culminated in the 1992 International Conference on Water and the Environment in Dublin, Ireland[4]. The NWRP also established an institutional framework[1,2] for managing water resources including the formulation of State Water Resources Councils, River Basin Committees and other bodies which support participatory management consisting of water resource stakeholders, government and agency representatives and citizens representing other Brazilian sectors.

Decision support tools are needed to support implementation of the NWRP and help manage Brazilian natural resources. Thus researchers, engineers and professionals involved in water resources management face the need to develop, improve and put in practice multiple tools for solving water quantity and quality problems including ecohydrological models such as those described in previous reviews[e.g.,5-7]. Among these models, the Soil and Water Assessment Tool (SWAT) watershed-scale ecohydrological model[8-10] has emerged as an effective tool for a wide range of hydrological and environmental assessments across different environmental conditions and watershed scales around the world. SWAT is a versatile model that encompasses different hydrological and agronomic components, and has been used by many government agencies and private firms to support decision making for water resource problems as well as university and other institutional teams engaged in cutting edge water quantity and water quality research[9,10]. An extensive array of different types of analyses has been performed with SWAT including climate change and/or land use change scenarios, improved irrigation strategies, the impacts of alternative best management practices (BMPs), adoption of bioenergy crops, the impacts of tile drainage on nitrate transport, and transport of sediment, nutrient, and/or pesticide pollutants[11-14].

SWAT's use and familiarity is expanding among Brazilian students, professors and professionals, which has resulted in dozens of hydrological and/or pollutant transport evaluations in Brazilian watersheds. The earliest documented application of SWAT in Brazil occurred in 1999[15]. Since then, well over 100 studies using SWAT in Brazil have been published in Brazilian and international journals, conferences and meetings proceedings, and as theses or dissertations, 60 of which were initially reviewed in a previous study[16]. Despite this application growth, most of the studies are limited to the academic environment and are focused on the capacity of the model to represent Brazilian watersheds adequately. Many of the studies have also been limited by a lack of detailed data in contrast with the large amount of information needed to describe the spatial and temporal variability of environmental systems (an especially acute problem in selected regions, depending on the study focus). Data collection and preparation for SWAT simulations in Brazil are usually time consuming, which poses challenges for conducting routine applications of the model.

Thus the specific objectives of this study are to describe: (1) the range of biomes, climatic zones and other environmental conditions that exist in Brazil, (2) an overview of Brazilian SWAT studies reported in the literature including the types of publications and studies, (3) trends in Brazilian SWAT applications, considering recent peer-reviewed English literature, (4) difficulties reported regarding lack of data for simulation inputs and model testing, (5) available regional, national, and international data sources that can be used for supporting SWAT applications in Brazil, and (6) future research needs and directions regarding the use of SWAT in Brazil.

3-2. Brazilian Biomes and Environmental Conditions

Brazil covers a total area of over 8.5 million km^2, is the largest nation in South America and the fifth largest nation in the world (both geographically and in population)[17]. Brazil is also classified as megadiverse in terms of biodiversity and is considered the most diverse country in the world in regards to terrestrial and freshwater resources[18]. The large territorial extent of the country encompasses several distinct biomes) which are dominated by varying vegetation including tropical rainforest (Amazonia)[19,20], thorn scrub and seasonally dry forests (Caatinga)[21], tropical savanna (Cerrado)[22-24], "hyperseasonal savanna" which experiences extended periods of flooding (Patanal)[25], seasonally dry or tropical rainforest (Mata Atlântica)[24,26] and grassland (Pampa)[27]. The tremendous biodiversity of these biomes are exemplified by: (1) Amazonia, which is one of the most biologically diverse regions worldwide[19], (2) the species-rich Mata Atlântica rain forest subregion, a global biodiversity hotspot that contains one of the highest percentages of endemic species in the world[26,28], and (3) the Cerrado region, which has been described as one of the 25 most important terrestrial hotspots on earth[23,28]. The Brazilian biomes also share the reality of intense environmental pressures including problems resulting by expanding agriculture in many subregions[19,21-24,26-28].

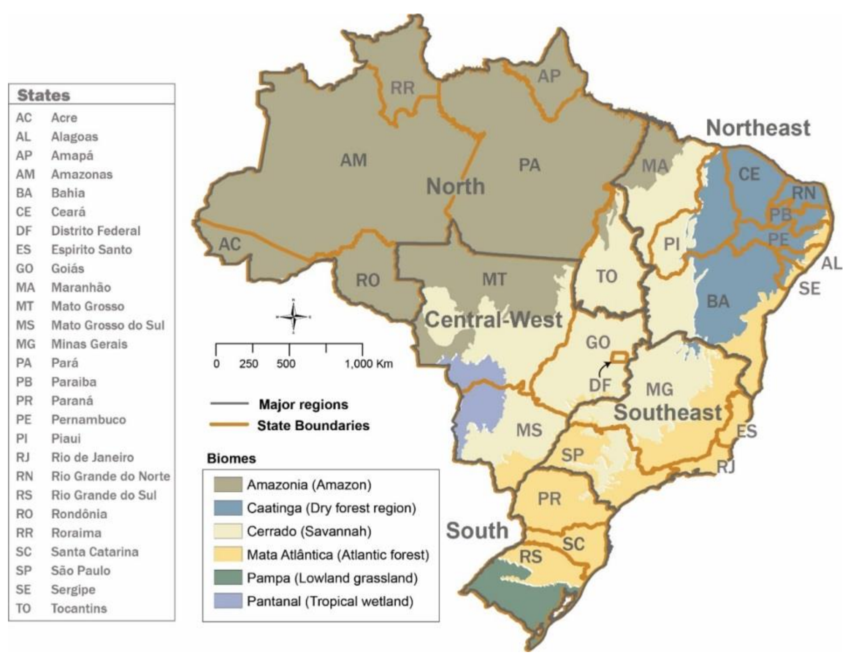

Figure 3-1 - Location of major geographical regions, states and biomes[29] in Brazil.

3-2.1. Climatic zones

Brazil is further characterized and classified by a complex mix of climate zones[30] adopted by the Brazilian Institute of Geography and Statistics (IBGE). It is structured per the following three classifications: (1) atmospheric circulation, with climatic zones defined as equatorial, tropical and temperate, (2) thermic regions which are delimited based on the frequency and average temperatures of the monthly extremes, and (3) classifications related to humidity and drought (Figure 3-1, Figure 3-2 and Figure 3-3). The average annual precipitation also varies strongly across the country (Figure 3-4), with high seasonality and spatio-temporal variability of rainfall in many regions which results in challenges regarding accurate representation by rain gauge networks and subsequent hydrologic simulations in models such as SWAT.

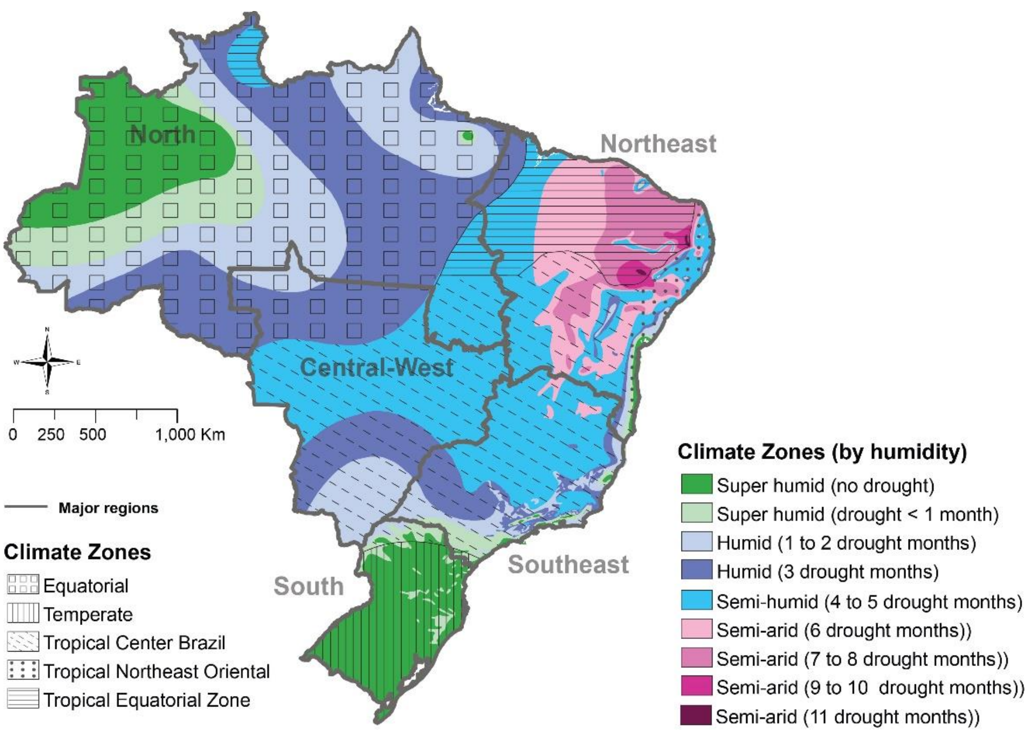

Figure 3-2. Location of major climate zones and humidity climate zones relative to the five major geographic regions of Brazil[31]

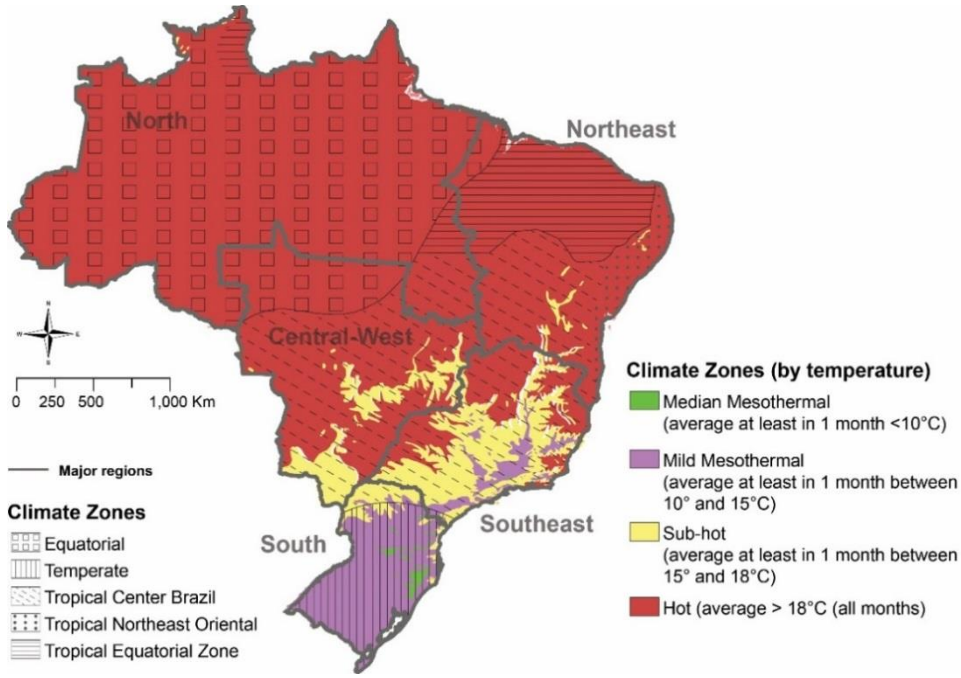

Figure 3-3 Location of major climate zones and temperature climate zones relative to the five major geographic regions of Brazil[31]

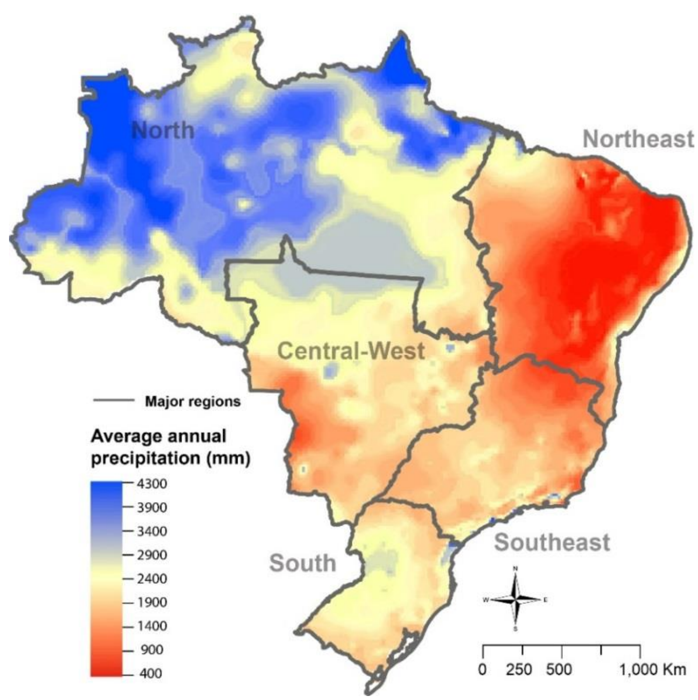

Figure 3-4. Distribution of mean annual precipitation relative to the five major geographic regions of Brazil[32]

The North region is located mainly in the Equatorial Zone (Figure 3-2) and is dominated by semi-humid to super humid conditions (Figure 3-2) consisting of a hot (Figure 3-3) climate and very high annual precipitation levels that exceed 4,000 mm in some subregions (Figure 3-4). Much of theNortheast region is classified as semi-arid (Figure 3-2) characterized by hot temperatures (Figure 3-3) with low annual variation and low average precipitation (Figure 3-4) with a short rainy season. However, some areas in the western part and along the coast are classified as humid or semi-humid, resulting in three climate zones (Figure 3-2): Tropical Equatorial Zone (north), Tropical Center Brazil (south) and Tropical Northeast Oriental Zone (northeast)[33].

The Central-West region is dominated by semi-humid to humid conditions, is primarily located in the Tropical Center Brazil Zone (Figure 3-2) and is further characterized by mostly hot weather and huge variability in annual precipitation levels ranging from a few hundred mm to nearly 3,000 mm (Figure 3-4). The Southeast region is also located in the Tropical Center Brazil Zone (Figure 3-2) and consists of humidity conditions ranging from semi-arid to super humid (Figure 3-2), a complex mix of subregional temperature zones classified as hot, sub-hot or milder mesothermal temperatures (Figure 3-3) and average annual precipitation levels generally around 1,500 mm with some smaller subareas that exceed 2,500 mm (Figure 3-4). The South region of Brazil is located within the Temperate Climate Zone and is dominated by super humid (Figure 3-2), mild mesothermal temperature climatic conditions (Figure 3-3) and relatively high mean annual precipitation levels (Figure 3-4) with much of the region averaging over 2000 mm.

3-2.2 Discharge characteristics

The distribution of water availability and average discharge ($m^3\ s^{-1}$) for the 13 major Brazilian river basins is shown in Figure 3-5[34]. Water availability is defined as equivalent to the flow duration curve of 95% (Q95); in case of reservoirs it is the regulated flow plus the Q95. The disparities in average discharge levels and water availability reflect the previously described climatic conditions, ranging from low discharge and water availability levels in the semi-arid region of the Brazilian Northeast to high discharge and water availability in the Amazon River basin in the North region (Figure 3-5). These extreme differences highlight the need for effective and efficient water resources management across the country, including the use of decision support and ecohydrological simulation tools such as SWAT.

3-2.3 Soil types

Brazilian soils are also very diverse and are the key components of the complex Brazilian natural resources panorama. Brazilian soil diversity is influenced by the different shapes and types of terrain, climate, parent material, vegetation and associated organisms[35]. Virtually every major type of soil exists in Brazil except for Gelisols, which contain permafrost, and Andosols, which develop due to deposits of volcanic ash[36]. The geologic and geomorphic origins of Brazilian soils differ greatly in comparison to soils formed in more temperate regions, such as in the U.S. and Europe[36,37]. Thus Brazilian soils are more naturally infertile and manifest typical tropical soil characteristics including deeper layers, high permeability, low cation exchange capacity, inadequate weatherable minerals (potassium, calcium, magnesium and phosphorus), high acidity and limited available soil water at planting time due to seasonal precipitation patterns[35-37]. However, it has been discovered that Brazilian soils have high agricultural potential and that the majority of land is suitable for farming (approximately 65% of the total territory of about 8.5 million km^2), assuming that adequate management levels are maintained[35]. Thus remarkable progress has occurred in recent decades in overcoming the natural limitations of Brazilian soils resulting in a massive expansion of intensive crop production and record grain productivity[35], especially in the Cerrado biome (Figure 3-1)[36,37]. Nevertheless, significant soil management challenges remain including serious soil erosion problems in several subregions of the country[38].

National-scale soil maps have been developed which show the distribution of major soil types across Brazil[39,40]. A Brazilian System of Soil Classification (SiBCS)[40] has also been developed that is based on previous regional soil surveys and features various texture, chemical and other soil-related characteristics[40,41]. The Brazilian Agricultural Research Corporation (EMBRAPA) has also compiled soil property data from surveyed soil profiles within the Brazilian Soils Information System which has recently been made available on-line (see Section and Appendix A). In spite of these efforts, refined soil surveys that describe specific soil series and integrate soil pedon data more directly with corresponding landscapes remain scarce for most Brazilian subregions[37]. This lack of detailed soil maps has potential implications for applications of SWAT and similar ecohydrological models in Brazil.

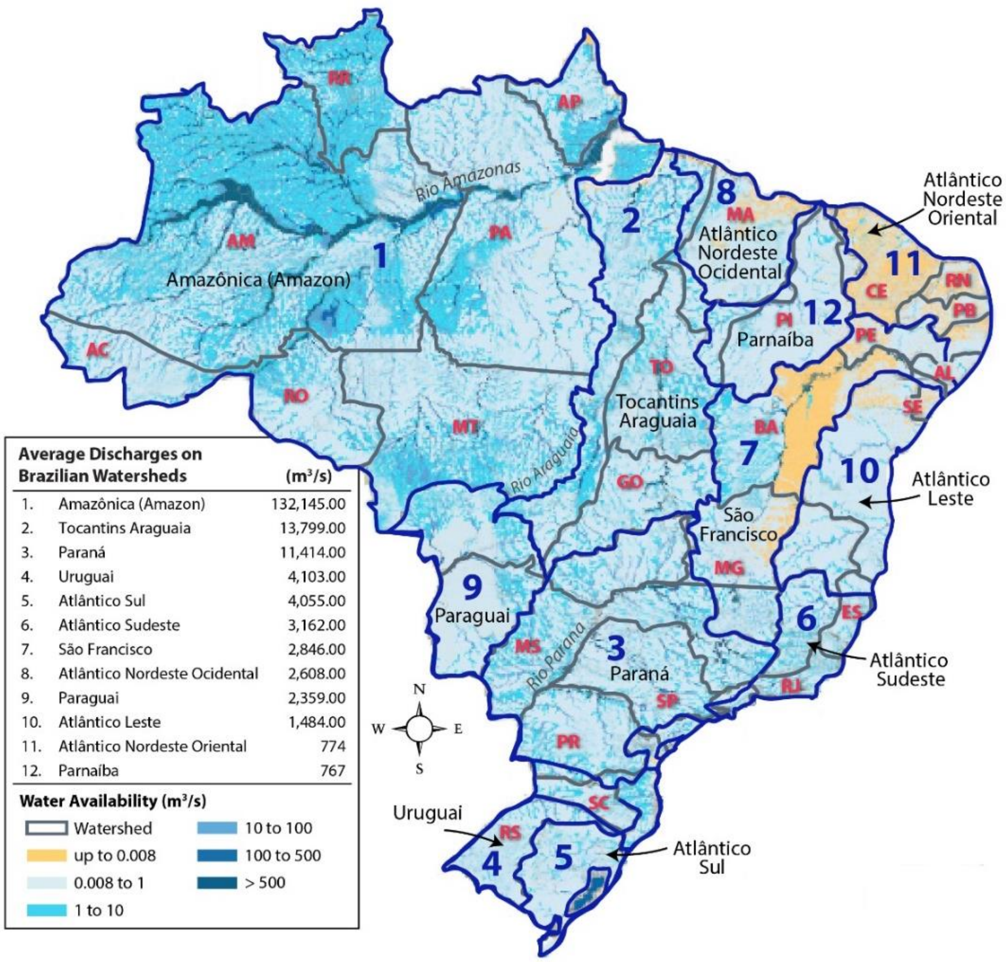

Figure 3-5 Spatial distribution of surface water availability by 12 major river basins or drainage regions and micro-basins within each the 12 major river basins or regions[30]

3-3. Overview of Surveyed SWAT applications in Brazil

A survey of published studies with SWAT in Brazil was conducted for a 14- year period (January 1999 to March 2013) which included peer-reviewed journal articles, conference proceeding papers, theses, dissertations and monographs written in Portuguese or in English. Theses and dissertations were only accounted for when published papers from the same study were not found. A total of 102 publications that report the use of SWAT in Brazilian watersheds were identified as a result of this survey[15,16,42-141].

The majority of the surveyed Brazilian SWAT studies were written in Portuguese (85%) with only 15% in English. About 18% of the studies were published as a thesis, dissertation or end of undergraduate course monograph versus 82% that were published in some type of paper format. Of those papers, 34% were published in journals, 60% in conference proceedings and 6% as expanded abstracts in conference proceedings. Many papers were published in proceedings of the Brazilian Water Resources Symposium (SBRH) and in the Northeast Water Resources Symposium (SRHN), both of which are sponsored by the Brazilian Water Resources Association (ABRH)[142]. Several SWAT-based studies have also been published in SWAT conference proceedings including the recent 2014 International Conference proceedings[143-145].

The distribution of the studies by year over the 14-year survey period is shown in Figure 3-6. The first study was published in 1999[15], followed by gradual adoption of the model over the next decade with a noticeable surge in increased use starting in 2009 (accounting of publications in 2013 and 2014 is incomplete due to the endpoint of the survey period). One factor underlying the increased use of the model in recent years are informal and formal SWAT training workshops conducted in 2011, 2012 and 2014 in Brazil, which are shown in Figure 3-7. In addition, growing networking opportunities, establishment of institutional partnerships and general broader awareness of the capabilities of the model via the SWAT website[146] are factors influencing increased usage of SWAT in Brazil. The expanding use of the model in Brazil is further evidenced by the preliminary results reported for Brazilian watershed conditions in over 45 SWAT-related studies that were presented at the 2014 International SWAT Conference[147].

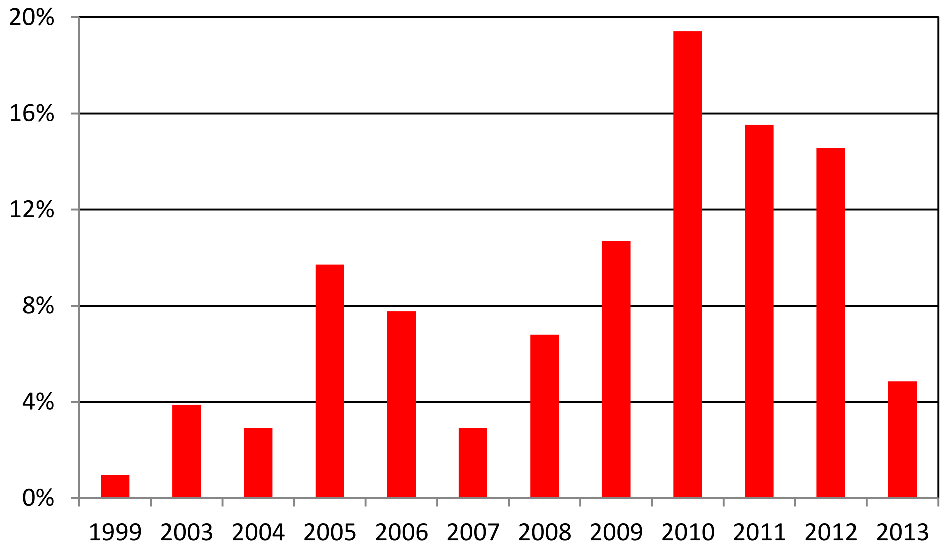

Figure 3-6. Distribution of the 102 studies identified in the Brazilian SWAT literature in percentage per year during the 14-year survey period (January 1999 to March 2013)

Figure 3-7 shows the spatial distribution of the 102 SWAT studies across the major geographic regions, biome regions and states. The majority of the studies were performed in the Mata Atlântica biome within the South, Southeastern or Northeastern regions, or to a lesser extent in the Cerrado biome. The overall distribution of studies clearly underscores the dearth of SWAT applications for the Amazon River basin region in the northern part of Brazil, which is a critical and highly sensitive hydrologic resource that drains 16% of the annual global river runoff[148] across approximately six million km^2, 63% of which is located in Brazil[149]. Despite these important hydrological conditions, the north region has a low density of hydrological monitoring networks which poses challenges for testing of models such as SWAT. However, abstracts reporting preliminary results of new SWAT studies for the Amazon River basin have been recently published[150-152], indicating that new research is emerging for the region.

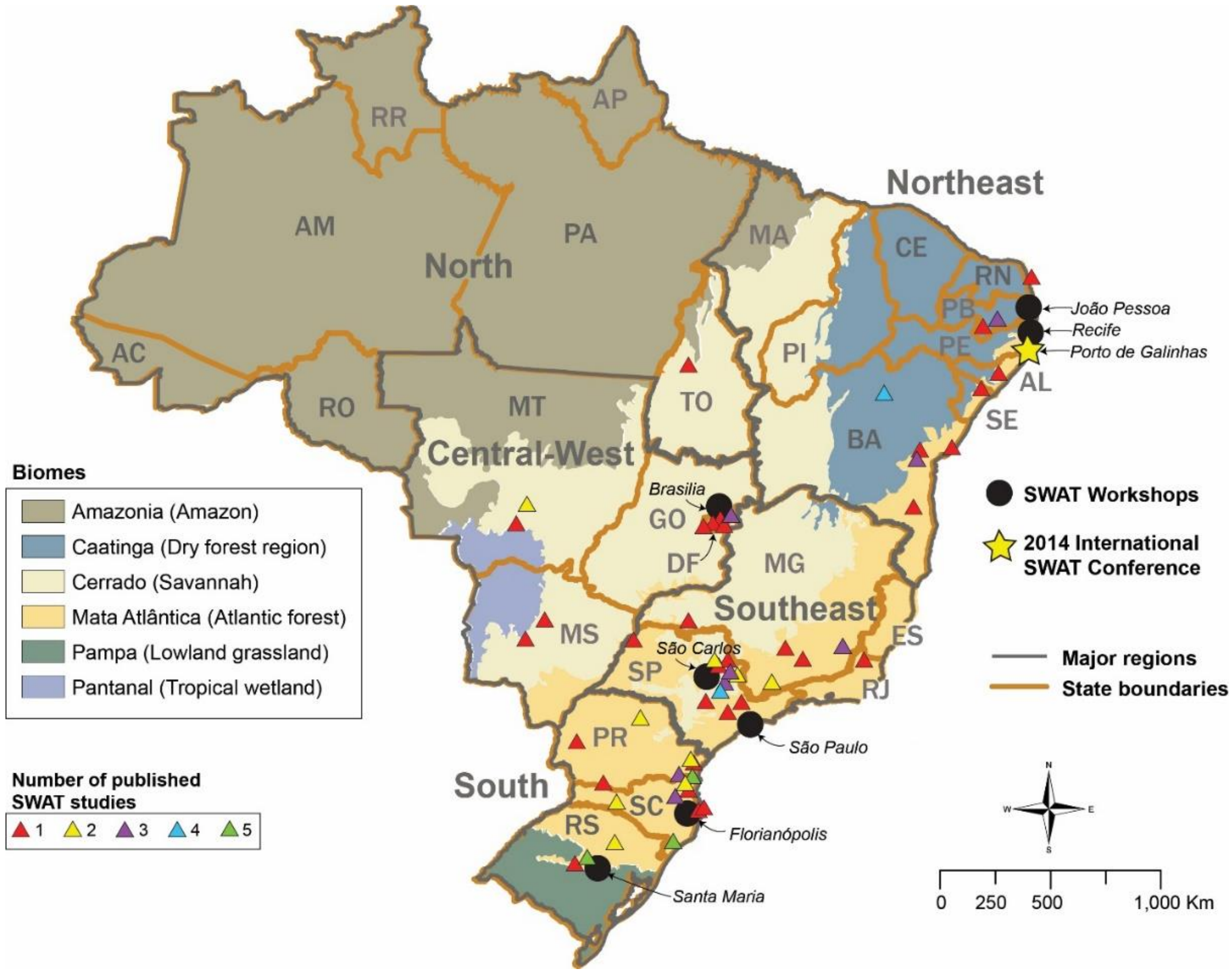

Figure 3-7.Distribution and number of Brazilian SWAT studies that were included in the literature survey, per the major geographic regions, biomes and states (state names are listed in Figure 3-1).

Figure 3-8 shows the percentages of SWAT studies performed per Brazilian region (Figure 3-8-a), state (Figure 3-8-b), type of simulation (Figure 3-8-c) and watershed drainage area (Figure 3-8-d). The highest concentration Of SWAT publications (34%) was for watersheds in the South region of Brazil, composed by the states of Paraná (PR), Santa Catarina (SC) and Rio Grande do Sul (RS) (Figure 3-1 and Figure 3-7), with a corresponding distribution of 8%, 24% and 8%, respectively (Figure 3-8-b). The second largest number of published studies (28%) of SWAT applications was in the Southeast region, which includes the states of Espirito Santo (ES), Minas Gerais (MG), Rio de Janeiro (RJ) and São Paulo (SP). The remaining 38% of SWAT studies were published for applications in the Northeast (22%), Central-West (10%) and North regions (1%), with only one study published in the North region.

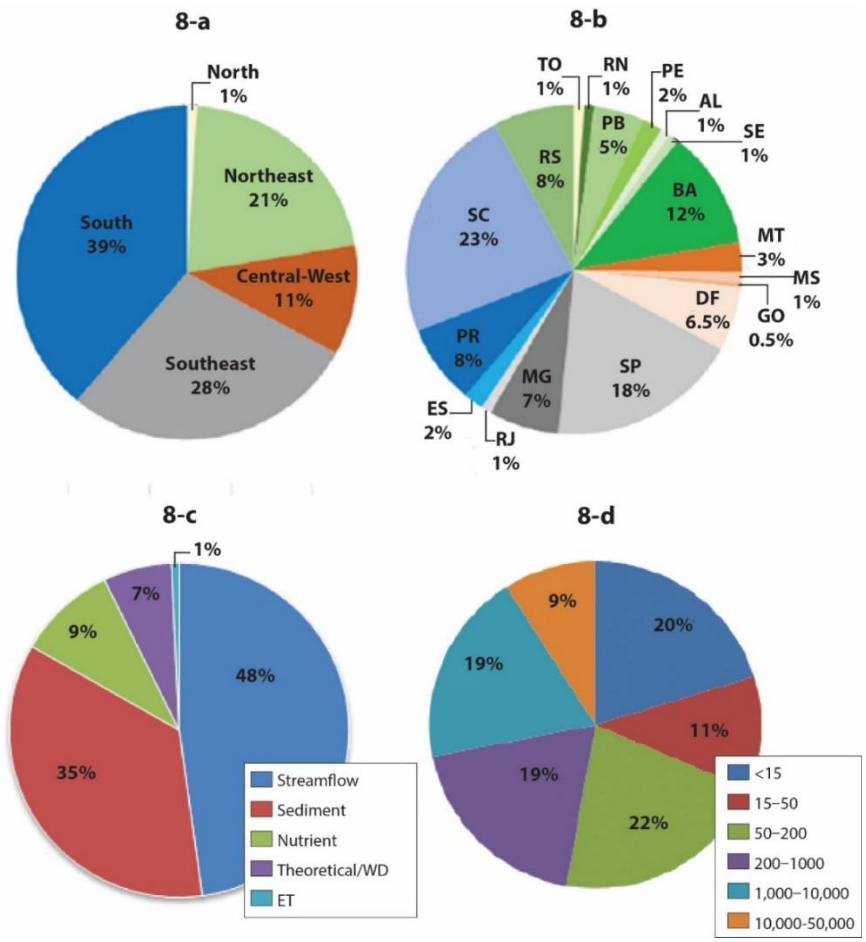

Figure 3-8 Percentage of publications using SWAT by: region (3.8-a), state (3.8-b), type of simulation (3.8-c) and watershed drainage area (3.8-d)

Only one SWAT-related study was published for the states of Tocantins (TO), Rio Grande do Norte (RN), Alagoas (AL), Sergipe (SE), Mato Grosso do Sul (MS) Goias (GO) and Rio de Janeiro (RJ), and only two studies were published for Pernambuco (PE) and Espírito Santo (ES). No SWAT-related publications were found for six of the seven states located in the North Region (Roraima (RR), Amapá (AP), Amazonas (AM), Pará (PA), Acre (AC) and Rondônia (RO)), and for three of the Northeast Region states of Maranhão (MA), Ceará (CE) and Piauí (PI).

The objective of the majority of studies identified in the existing literature was to test the feasibility of applying SWAT for specific watersheds in Brazil. Several of the published studies also report various scenario results, especially outcomes of evaluating different land use scenarios. The publications were classified based on the following five categories: streamflow, sediments, nutrients/pesticides, theoretical/review papers or those related only to watershed delineation (theoretical/WD), and evapotranspiration (ET). The distribution of the studies according to these five categories is shown in Figure 3-8-c; studies that reported both streamflow and sediment loss/transport results were classified in both categories. The largest percentage of SWAT investigations focused on streamflow (48%) and/or sediment loss and transport (36%). There were only a few studies that reported nutrient transport results (9%) and even fewer that focused on theoretical/WD aspects (6%) or the effects of ET methods (1%). The state with the most SWAT water quality (nutrients and pesticides) studies is Paraná (PR; Figure 3-1 and Figure 3-7), which is also the only state where a governmental agency applied SWAT for a water quality application[16].

Many of the studies focused on SWAT simulations of small watersheds, some of which are experimental watersheds (managed by universities or government agencies). The percentage of publications per watershed size is presented in Figure 3-8-d; 20% of the studies were conducted in watersheds < 15 km² in area, 72% in watersheds < 1,000 km² in area, and only 9% in watersheds > 10,000 km². This distribution underscores the fact that there are extensive needs and opportunities regarding applications of SWAT for large-scale river basin systems in Brazil.

The smallest watersheds modeled with SWAT were: (1) a 0.1 km^2 experimental watershed located in the larger Alto Negro River watershed in the state of Santa Catarina[77], and (2) a 0.91 km² watershed located in the semi-arid Caatinga (dry forest) biome region in the state of Paraiba (Figure 3-1 and Figure 3-7) that consisted of a mix of native vegetation and agriculture[118]. The largest simulated watershed among the surveyed studies was the 29,000 km^2 Cuiabá River watershed in Mato Grosso[52]. However, not all of the studies reported the size of the simulated watershed areas. Also, several recent studies have reported SWAT applications for very large Brazilian river systems including parts or all of the Amazon River basin[150-152], the São Francisco River basin[153-156] and the Jaguaribe River basin[157,158].

About 66% of the studies presented SWAT calibration results and only 23% also presented SWAT validation results. The distributions of the number of years used for the calibration and validation periods are presented in Figure 3-9, for those studies that reported such information. The fact that calibration and/or validation was not reported or that small time periods were used for many of the studies (~70% of studies that reported calibration and validation used less than 5 years for each), may indicate difficulty in obtaining adequate model testing data for many subregions of Brazil. This could be due to limited or no observed data and/or observed data consisting of insufficient quality. It is also possible that some studies were of a preliminary nature and thus extensive testing was not considered necessary.

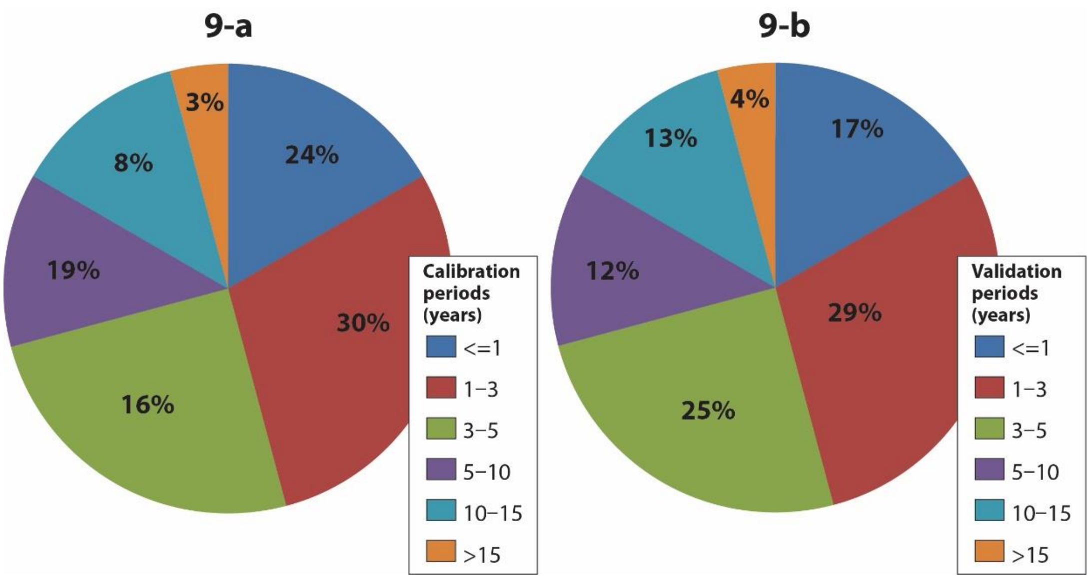

Figure 3-9 Distribution of studies, which reported calibration or validation results, based on time periods used for (a) calibration and (b) validation

The Nash-Sutcliffe modeling efficiency (NSE)[159] is one of the most widely used statistical measures used to evaluate the accuracy of SWAT simulation results[10-13,160]. Previous research[160] resulted in suggested criteria for judging the performance of hydrological and water quality models, including a key criteria that NSE values should ≥ 0.5 for aggregated monthly time step evaluations. The authors further suggest that appropriate adjustments for daily or annual time step evaluations could be made and provide additional criteria for good and very good ratings[160]. The NSE results were tabulated for those surveyed studies that reported NSE values (Table 3-1) and evaluated per the suggested criteria[160] , assuming that both the monthly and daily NSE values should be ≥ 0.5. The results in Table 3-1 show that nearly 95% of the studies reporting monthlycalibration/validation NSE statistics met the satisfactory criteria, with 61% of the calibrated NSE values achieving the "very good" criteria. However, weaker results were found for the overall subset of daily calibration/validation NSE statistics, with 75% of the NSE values considered satisfactory and 25% that achieved the very good criteria. The statistical results for some of the studies clearly indicated poor model performance which could have occurred for several reasons including inadequate representation of the simulated system in SWAT, inaccurate input data, weakness in some of the SWAT algorithms or inadequate measured data used for model testing.

Table 3-1. Nash-Sutcliffe (NSE) performance ratings for surveyed studies that reported hydrologic calibration statistical results

Performance Rating[a]	NSE criteria[a]	Monthly NSE (31studies)	Daily NSE (26 studies)
Very Good	0.75<NSE≤1.	61%	25%
Good	0.65<NSE≤0.	29%	18%
Satisfactory	0.50<NSE≤0.	3%	25%
Unsatisfactory	NSE≤0.50	6%	25%

[a]Suggested criteria for judging model NSE results based on a monthly time step[160], which is used here also to evaluate the daily time step NSE results

3-3.1. Further insights regarding the surveyed Brazilian SWAT literature

The first identified SWAT study published in Brazil[15] indicated that SWAT could be used for planning and management in Brazilian watersheds. Other later studies also concluded that it had great potential as an assessment tool[46,47] for watershed management in Brazil[e.g.,56,69,70,90]. SWAT was also applied and/or indicated as a potential tool for water resources and forestry policy assessments in Brazil[56,69,98], and was applied for other scenario assessments in several studies [e.g.,43,52,55,64,79,89,90,100,122,136]. Many of the SWAT studies focused on production and transport of sediment[e.g.,49,67,70,73,84,92,94,102,112,121,122,132,141]; some concluded that SWAT was able to perform well in general[e.g.,44,79], and one study[84], due to sediment data limitations, concluded that their results could only be used in a qualitative rather than a quantitative manner.

Only a few Brazilian studies reported pesticide or nutrient water quality analyses (Figure 3-9-a). One study evaluated the biogeodynamics of pesticides employed in sugarcane production and stated that SWAT can adequately simulate herbicide behavior, when calibrated and validated[62]. Nutrient cycling and transport simulations were conducted as part of a study conducted for Bonito river subbasin[59,61] in the Pantanal biome (Figure 3-1 and Figure 3-7), which resulted in good statistical results for predicted nitrogen and phosphorus losses. A study performed for the Concórdia watershed[82] reported streamflow, sediment and nutrient evaluations, but concluded more detailed information about effluent discharges and residue management were needed to better represent the simulated system. Streamflow and phosphorus were simulated for the Conrado and Pinheiro River watersheds, resulting in outcomes that were considered acceptable[95]. Another study recommended careful use of SWAT for nutrient simulations in tropical watersheds based on testing of fertilizer scenarios[96].

Other types of SWAT applications were described among the surveyed literature including evaluation of the effects of DEM resolution on SWAT results[101], evaluation of evapotranspiration methods[50], sensitivity analysis of various parameters[53,91,119], estimation of flow duration curves[65,135], heat flux estimated with the SEBAL model from satellite images combined with SWAT output[104], simulation of an area with intense irrigated rice farming[78], comparisons of different precipitation input and infiltration methods[72,74], assessment of best management practices on streamflow[141] and estimation of low flows spatial variability[88]. At least three hydroelectric plant-related applications of SWAT have also been reported[16]. Anecdotal information indicates several governmental and private institutions (e.g.; ANA, Epagri, and EMBRAPA) have used SWAT although documentation is currently lacking in the literature[16].

3-4. An In-Depth Look at Recent English Brazilian SWAT Literature

Table 3-2 summarizes 19 peer-reviewed Brazilian SWAT studies written in English that were reported in the literature between 2012 and early 2015. Over half of these recent studies were published after the end of the previously described 14-year survey of Brazilian literature, indicating that the Brazilian peer-reviewed English SWAT literature is definitely expanding. This subset of SWAT studies reflect some of the dominant trends found in the surveyed literature including the majority being conducted in the South and Southeast regions (>60%) and most reporting only hydrologic results or just sediment outputs, if pollutant transport was also simulated. However, the studies listed in Table 3-2 also represent expanded scenario analyses (e.g., blue/green water[161], BMP impacts[141,163-165], land use change[154,164,165]) and other key types of analyses (e.g., impacts of alternative precipitation sources[128,148,162]; modified SWAT versions that more realistically replicate specific physical processes[130,135,141]) which mirror broader global SWAT application trends and reflect growth in the overall domain of Brazilian SWAT applications.

Table 3-2. Selected recent studies published in English between 2012 and 2015 which reflect key SWAT application trends in Brazil

Study	Application emphasis	Watershed name (size shown in km^2)	State[a]	Part of survey?
141	BMP analysis	Pipiripau River (235)	Distrito Federal	Yes
163	BMP analysis	Sao Bartolomeu (54)	Minas Gerais	No
161	Blue/green water analysis	Cachoeira River (291)	São Paulo & Minas Gerais	No
123	Climate change	Concordia River (30.74)	Santa Catarina	Yes
128	Climate data effects	Pipiripau River (215)	Distrito Federal	Yes
158	Climate data effects	Jaguaribe River (73,000)	Ceará	No
162	Climate data effects	Rio Groaíras (1,044)	Maranhão	No
115	Hydrologic analysis	Paraopeba River[b]	Minas Gerais	Yes
135	Hydrologic analysis	Arroio Lino (4.8)	Rio Grande do Sul	Yes
166	Hydrologic analysis	Galo Creek (943)	Espírito Santo	No
167	Hydrologic analysis	upper Itapemirim River (2,237)	Espírito Santo	No
164	Land use effects	Galo Creek (943)	Espírito Santo	No
165	Land use effects	Pará River (12,300)	Minas Gerais	No
121	Sediment transport	Arroio Lino (4.8)	Rio Grande do Sul	Yes
122	Sediment transport	"Rural" (1.19)	Rio Grande do Sul	Yes
154	Sediment transport	São Francisco River (630,000)	Multiple states[c]	No
168	Sediment transport	Mamuaba (60.9)	Paraiba	No
169	Sediment transport	Lavrinha Creek (6.88)	Minas Gerais	No
130	Vegetation growth	Santa Maria/Torto (234)	Distrito Federal	Yes

[a]See Figure 3-1 for locations of each respective state.

[b]Watershed size not reported.

[c]Drains portions of the states of Minas Gerais, Bahia, Pernambuco, Alagoas, Sergipe, Goiás and the Federal District.

3-4.1. SWAT hydrologic testing

Four of the studies were identified as specifically focusing on baseline hydrologic analyses[115,135,164,166]. However, all but one of the 19 studies shown in Table 3-2 report some level of SWAT hydrologic calibration. Fourteen studies[115,122,123,128,130,135,141,161,162,164,165,167-169] reported unique NSE values based on daily comparisons between predicted and measured streamflows. Approximately 75% of the reported daily calibration or validation NSE values across the 14 studies exceeded the previously described suggested criteria of NSE ≥ 0.50[160] for satisfactory hydrologic modeling results, similar to the tabulated results for the surveyed Brazilian SWAT studies (Table 3-1). The extensive reporting of successful daily streamflow results within this subset of studies (Table 3-2) reflects an overall trend of increased satisfactory daily SWAT streamflow testing results reported in recent peer-reviewed literature[11-13].

Four studies[128,154,158,162] (Table 3-2) provide insights regarding the effects of using different precipitation sources in the context of SWAT hydrologic baseline testing. Four different precipitation datasets were analyzed with SWAT for the 215 km^2 Pipiripau River[128] located in the Distrito Federal (Figure 3-1), varying in terms of data source (rain gauge or Tropical Rainfall Measurement Mission (TRMM) 3B42[170] satellite data), spatial distribution (lumped or distributed), and temporal distribution (raw time series or moving average), Satisfactory streamflow estimates resulted for all four sets of precipitation data sources but the strongest results were obtained using ensemble combinations of the individual streamflow estimates[128]. Local rain gauges, TRMM 3B42 data and a second satellite data source were all found to result in acceptable SWAT streamflow estimates for the 1,044 km^2 Rio Groaíras watershed located in Maranhão[162] (Figure 3-1). Four combinations of climate data were analyzed for the 73,000 km^2 Jaguaribe River[158] located in Ceará (Figure 3-1) that included three sources of rain gauge-based precipitation data, other climate data available from specific climate stations, climate data generated from the Climate Forecast System Reanalysis (CFSR) global forecast model[171,172] and/or climate data generated internally in SWAT. The most accurate streamflow estimates resulted from using local rain gauges in tandem with CFSR non-precipitation climate inputs while the least accurate results occurred using CFSR precipitation data in combination with other CFSR climate inputs[158]. CFSR precipitation data also resulted in unsatisfactory streamflow results for 630,000 km^2 São Francisco River study[154] (Figure 3-5); more reliable streamflow results were obtained using rain gauge precipitation data.

Other sources of hydrologic uncertainty were implied among the studies shown in Table 3-2 including: (1) a 5-year warm-up period resulted in more reliable SWAT streamflow estimates versus a one-year warm-up period for the Jaguaribe River study[158], indicating that sensitivity analyses could be needed for some watershed systems to determine an adequate warm-up period length, (2) the analysis of the São Francisco stream system[154] (Figure 3-5) revealed that different input parameter values had to be defined for subbasins located in the Caatinga biome versus the Cerrado biome (Figure 3-1), and (3) the need for more accurate simulation of tropical perennial vegetation by applying a modified SWAT model to the 234 km^2 Santa Maria/Torto River watershed[130], located within the Distrito Federal (Figure 3-1). The improved simulation of tropical perennial vegetation was accomplished by using specific thresholds of simulated soil moisture (rather than dormancy) to determine the end of a growing season and by replacing the linear LAI decline function with a more realistic logistic LAI decline towards the user-defined minimum LAI value. The results indicate that the modified SWAT model can accurately replicate Cerrado biome (Figure 3-1) perennial vegetation growth patterns, is transferable to other tropical regions and that inaccurate representation of perennial vegetation growth may be occurring in many tropical region SWAT applications.

3-4.2 SWAT pollutant loss testing

Only eight studies (Table 3-2) report some type of sediment prediction testing[121-123,141,154,163,168,169] and only one study reports the results of evaluating nutrient loss predictions[163]. A variety of graphical and statistical methods were used to evaluate the SWAT sediment output including the statistics shown in Table 3-3.

Three of the studies (Table 3-3) reported generally weak sediment testing results, with the majority of NSE values < 0 [121,122,141]. Very poor results were found for a small 1.19 km^2 watershed in Rio Grande do Sul[121] (Figure 3-1), due to SWAT's inability to replicate overall runoff accurately, including important sub-daily hydrologic processes, resulting in excessive over-estimation of sediment loss. Calibration period NSE values were mostly positive but all of the validation NSE statistics were negative for the analysis of multiple precipitation sources for the Pipiripau River (Table 3-2), indicating that SWAT was not able to replicate the measured data which were based on sediment rating curves[141]. However, fundamental problems with estimating sediment rating curves were noted implying that there were likely large inaccuracies in the measured data. The application of a modified "SWAT-landscape" model[121] resulted in improved representation of sediment deposition and transport processes versus the standard SWAT model for the steeply sloped 4.8 km^2 Arroio Lino watershed in Rio Grande do Sul (Figure 3-1). Some weakness was still evident per the validation phase for the modified model, although the statistical results greatly improved relative to the standard SWAT model (Table 3-3).

3-4.3. Overview of scenario results

A blue/green water assessment was performed with SWAT for the 291 km^2 Cachoeira River watershed in São Paulo and Minas Gerais[161] (Figure 3-1) using previously described "blue water" and "green water" concepts[175]. The results of the analysis showed that conditions of water scarcity and vulnerability exist both spatially and temporally within the watershed and that more stringent Environmental Flow Requirements (EFR) procedures are required to better manage available water resources in the study region.

The impacts of two different climate change scenarios on streamflow and sediment loss were simulated with SWAT for the small 30.7 km^2 Concordia River[123] located in Santa Catarina (Figure 3-1). The simulated climate projections were based on standard "A2" and "B2" scenarios that were developed by the Intergovernmental Panel on Climate Change (IPCC)[177], and were representative of the 2071 to 2100 future time period. The overall hydrologic impacts of the two scenarios were similar, with both predicted changes in future climate resulting in roughly a 40% decline in streamflow. The predicted cumulative future sediment losses differed markedly between the two scenarios, with very little change predicted for the A2 scenario versus an estimated 20% decline in total sediment loss in response to the B2 scenario.

Table 3-3. Selected statistics for the studies that reported baseline sediment testing results

Study	Time step	Calibration or validation	Time period (years)	NSE[a]	R^2	PBIAS (%)
121 (standard)	annual	calibration	1	-0.10	0.70	-84.0
	annual	validation	1	-12.10	0.50	-63.0
121 (modified)[b]	annual	calibration	1	0.70	0.80	-14.0
	annual	validation	1	-1.40	0.60	-22.0
122	daily	calibration	1	-7.80 to -145.60[c]		
	monthly	calibration	1	-6.50 to -241.60[c]		
123	daily	calibration	0.6	0.31		
	monthly	calibration	0.6	0.83		
141	daily	calibration	2	-0.10 to 0.42[d]	0.09 to 0.42[d]	-12.0 to 8.0[d]
	daily	validation	2.5	-0.70 to -9.20[d]	0.07 to 0.52[d]	-159.0 to 70.0[d]
154	monthly	calibration	6			11.6
	monthly	validation	4			-22.6
163	monthly	calibration	1	0.90	0.91	
168	monthly	calibration	4		0.66	
169	daily	calibration	2	0.68		
	daily	validation	2	0.75		

[a]NSE = Nash-Sutcliffe modeling efficiency[159,160].

[b]See previous studies[173,174] for further description of the modified SWAT model.

[c]Five daily and monthly NSE statistics were computed for each of five years.

[d]Five statistics were computed for four different precipitation sources and the ensemble mean of the individual predictions.

The general conclusion of the other five studies[123,154,163,168,169] was that SWAT adequately replicated the measured sediment yields for the simulated conditions, and satisfactory results were also reported for the only study that presents evaluations of baseline SWAT-predicted total nitrogen (TN) and total phosphorus (TP) losses[163]. The assessment of the accuracy of the large São Francisco River system was based primarily on monthly PBIAS results (Table 3-3), which the authors note would be categorized as "good results" per previously suggested criteria[160]. They also provide an overall sediment balance analysis of sources and sinks that provides further confirmation of the accuracy of their baseline results.

A SWAT BMP assessment of terrace, sediment retention basin and multi-diverse crop rotation impacts on streamflow and sediment transport was performed for the Pipiripau River watershed[141] using the same precipitation input ensemble as described above[128]. The authors modified SWAT in order to more accurately account for the use of small sediment retention basins that are typically installed along roads to capture surface runoff and sediment. The results for the ensemble mean varied greatly as highlighted by the following three scenarios [128,141]: (1) adoption of a complex 8-year rotation with 11 different crops on 50% of the cropland resulted in streamflow and sediment reductions of 43% and 21%, (2) installation of terraces on 100% of the agricultural areas resulted in streamflow and sediment reductions of 0.6% and 31%, and (3) implementation of sediment retention basins along 100% of the road network resulted in streamflow and sediment reductions of 0.06% and 22%.

An extensive suite of BMPs was simultaneously simulated in a SWAT application for the 54 km^2 Sao Bartolomeu River watershed in Minas Gerais (Figure 3-1), which included accounting of pasture resting periods, contour farming, crop rotation and intercropping, improved use of fertilizers and manure inputs, revegetation and terracing on agricultural areas and depiction of permeable pavements, infiltration wells and green roofs in urban areas[163]. The cumulative effects of the combined set of BMPS resulted in 18%, 66%, 25% and 30% average annual reductions at the watershed outlet for runoff, sediment yield, TN and TP, respectively.

Three land use scenarios were compared relative to baseline conditions using SWAT for the 943 km^2 Galo Creek in Espirito Santo (Figure 3-1) over a seven-year period[164]. A key aspect of the land use scenarios was the amount of forest present, which ranged from almost 0% to 97% and was represented by forest vegetation that is native to the Mata Atlântica biome (Figure 3-1). A scenario which depicted that legally mandated permanent preservation areas (PPAs) were actually covered by native forest (PPA regulations are not always followed) resulted in a reduction of runoff of almost 6%. A second scenario which represented conversion of nearly all of the land use to forest, resulted in a runoff reduction of over 11%. Opposite trends occurred when virtually all of the land use was converted to pasture. A similar land use impact study was conducted with SWAT for the 12,300 km^2 Pará River watershed[165], a tributary of the São Francisco River located in Minas Gerais (Figure 3-1 and Figure 3-5). The authors compared original land cover in the watershed, which was dominated by native Mata Atlântica biome forest and Cerrado biome vegetation (Figure 3-1), versus current land use which included 38% pasture, 7.5% eucalyptus tree forest and 4.5% agriculture, and further represented overall declines of about 50% and 25% of the original Mata Atlântica and Cerrado vegetation. It was concluded that the conversion of native vegetation to the current mix of land use has resulted in a 10% increase of streamflow at the watershed outlet.

A novel SWAT historical land use impacts scenario was performed for the entire São Francisco River basin (Figure 3-5) by converting a calibrated SWAT baseline model of present day conditions to represent pre-European development land use and stream management conditions (circa 1850)[154]. The analysis revealed that there have been large erosion increases from stream beds (158%), stream banks (342%) and upland or tributary sources (332%) since the mid-1850s. Conversely, decreases were predicted for several sediment sinks since the beginning of the European settlement period, including deposition in stream beds (-187%) and on floodplains (27%), as well as export to the Atlantic Ocean (-54%). However, increases of 54 million t of sediment per year were predicted for sediment deposited in reservoirs, indicating that the reservoirs are functioning as large sediment traps.

3-5. Brazilian Databases for SWAT Applications

Many of the studies reviewed here described difficulties in applying SWAT for Brazilian watersheds due to a lack of data availability, a lack of easily accessible forms of data that have been compiled and/or problems related to the processing of data required for the model application[e.g.,16,42,45,54,57,58,65,83,84,90,116,117,120,135,157]. Much of the existing data is not well organized, is not accessible via centralized databases or exists in formats that are not readily useable in the ArcSWAT Geographic Information Systems (GIS) interface[177] or other pre-processing tools that are used to build SWAT input data sets. The lack of available data or easily accessible data at the required precision, quality and resolution is a particularly acute problem for certain subregions of the country (e.g., Amazonia). These data constraints result in the need to perform theoretical parameterizations for many SWAT applications in Brazil. An example of such parametrizations is the use of pedo-transfer functions in many studies to estimate parameters of Brazilian soils to run SWAT.

At the same time, extensive efforts have been conducted or are underway to organize more easily accessible national-level databases in Brazil by several federal agencies including a web-based hydrologic database developed and/or gathered by the National Water Agency (ANA), weather database by the National Institute of Meteorology (INMET) and a soil database assembled by the Brazilian Agricultural Research Corporation (EMBRAPA). Other insightful maps and information about Brazil can be found in IBGE's Brazilian National Atlas of 2010[178] and the Brazilian Army Geographic Database[179]. Further regional, state or local level data have been compiled by a variety of agencies, universities and other organizations. The use of SWAT in Brazilian watersheds should thus be preceded by an evaluation of the available data for the planned study region including: (1) national databases such as those constructed by ANA, IBGE, INMET and EMBRAPA, (2) regional, state, university and private data resources, and (3) previous studies in the region.

Table 3-4 to Table 3-8 present global, national, state and other sources of climate/hydrological, digital elevation map (DEM), land use and soil data that are available to support SWAT applications in Brazil, along with example studies that report using the various data sources. It is expected that this overview of data sources will serve as a useful resource for scientists and others who already are using SWAT, or plan to use the model in the future, in Brazil. Brazil also has a federal law (Law 12,527 of 2011) that regulates the right to obtain public information; thus if a certain study or station belongs to a government agency, information for that study can be accessed via an "Access to information" request[180]. Weblinks are provided in Appendix A that provide internet locations where interested potential users can either access data directly or learn more about the how to obtain various data from government agencies and other sources.

Table 3-4. Climate and hydrological data sources for Brazilian SWAT applications

Institution/Agency	Extent of coverage[a]	Studies reporting use of data
NCEP-CFSR (National Centers for Environmental Prediction - Climate Forecast System Reanalysis)	Global	158
INMET (National Institute of Meteorology)	National	42, 52-55, 57, 58, 65, 75, 78, 83, 88, 130, 136, 158
EMBRAPA (Brazilian Agricultural Research Corporation)	National/regional	47, 61, 128, 141
SIMEPAR (Paraná State Meteorological System)	Paraná	56, 66, 69, 95
UNESP (State University of São Paulo)	São Paulo	62
UFMT (Federal University of Mato Grosso)	Mato Grosso	52, 112
Battistella Florestas Company	Paraná	74
Coruripe Plant	Alagoas	67
Epagri/Ciram (Santa Catarina Agricultural Research and Extension Corporation)	Santa Catarina	73, 78, 80, 82, 83, 88, 90, 98, 138
USP (University of São Paulo)	São Paulo	43, 44, 62, 64, 68
ANA (National Water Agency)	National	42, 52-54, 56-58, 66, 67, 78, 80, 83, 84, 87, 136, 141, 158
ANEEL (Brazilian Electricity Regulatory Agency)	National	45, 79
DAEE (Department of Water and Electrical Energy)	São Paulo	43, 44, 62, 64, 68, 161
SABESP (Basic Sanitation Company of the São Paulo State)	São Paulo	161

[a]See Figure 3-1 for locations of specific states within Brazil.

Table 3-5. Digital Elevation Map (DEM) data sources for Brazilian SWAT applications

Institution/Agency	Extent of coverage[a]	Example studies reporting use of data
SRTM (Shuttle Radar Topography Mission)[b]	Global	67, 85, 97, 101, 158
ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer)	Global	----
IBGE (Brazilian Institute of Geography and Statistics - Topographic maps)	National	42, 47, 49, 50, 53, 54, 57-59, 61, 65, 80-82, 90, 94, 95, 102, 138
CODEPLAN (Development Central Plateau Company)[181]	Distrito Federal	128, 130, 141

[a]See Figure 3-1 l for locations of specific states within Brazil.

[b]A SRTM version also exists that has been corrected by EMBRAPA for Brazil (see Appendix A)

Table 3-6. Land Use Map data sources for Brazilian SWAT applications

Institution/Agency	Extent of coverage[a]	Example studies reporting use of data
USGS (United States Geological Survey - Land Cover Dataassemble several links to data sources)	Global	----
FAO (Food and Agriculture Organization) Global Land Cover-SHARE (GLC-SHARE)	Global	----
INPE (National Inst. for Space Research)[182,183]	São Paulo	----
Bahia State Company of Urban Development	Bahia	97
IAC (Agronomic Institute of Campinas)	São Paulo	55
FATMA (Environmental Foundation)[184,185]	Santa Catarina	90, 98
PARANASAN project[186]	Paraná	34, 45
LANDSAT satellite images	Global	42, 45, 47, 52-54, 65, 78, 79, 83, 88, 95, 128, 130, 136
SPOT satellite images	Global	43, 44, 64, 68, 82
Orthophotographs	Global	73, 75
IKONOS satellite images associated with field surveys	Global	102

Table 3-7. Land Use Map data sources for Brazilian SWAT applications

Institution/Agency	Extent of coverage[a]	Example studies reporting use of data
Produtor de Água project[187]	Pipiripau River Basin	141
Field Surveys	Local	81
From previous studies	Local	49, 50, 59, 61

[a]See Figure 3-1 for locations of specific states within Brazil.

Table 3-8. Soil Map and properties data sources for Brazilian SWAT applications

Institution/Agency	Extent of coverage[a]	Example studies reporting use of data
FAO-UNESCO (Food & Agriculture Organization-United Nations Educational, Scientific and Cultural Organization)	Global	----
Project RADAMBRASIL (Brazilian Government)	National	15, 57, 58, 97, 158
EMBRAPA (Brazilian Agricultural Research Corporation)	National	43, 44, 64, 67-69, 73-75, 78, 80, 82-84, 88, 90, 98, 102, 138
Digital Pedalogical Map[188]	Distrito Federal	128, 130, 141
ISRIC (World Soil Information)	Global	158
IAC (Agronomic Institute of Campinas)	São Paulo	43, 44, 55, 64, 68
Emater-RS	Rio Grande do Sul	81, 94
SEMA-Environmental State Foundation	Mato Grosso	52, 112, 136
Watershed Committee: Alto Paraguay Basin Conservation Plan[189]	Alto Paraguay River basin	46
Integrated management project for the São Francisco Watershed supported by ANA	São Francisco River basin	56-58
Water Resources Master Plan for Bahia State	Bahia	53, 54, 63
Paraná Federal University (studies)	Paraná	66
Soils data from previous studies	Local	49, 50, 59, 61, 65, 75
Soil sample analyses	Local	90, 98

[a]See Figure 3-1 for locations of specific states within Brazil.

3-6. Future Research Needs and Directions

The review presented here underscores that SWAT has proven to be a robust research and investigation tool for many types of hydrological and water quality applications in Brazil. However, it is also clear that there remain many data and research gaps that impede routine use of the model for Brazilian conditions. The complex array of biome, climate and other natural conditions presents further challenges regarding more widespread and reliable adoption of the model across the country. These realities point to a number of SWAT research, testing and developmental needs, regarding expanded future applications in Brazil, which can improve application of the model and provide enhanced guidance and support for Brazilian policy and decision makers, including the following:

1) Large System Modelling: Many of the studies discussed here report SWAT applications for relatively small watersheds. Although small-scale applications are important for developing models that can realistically perform across a range of different environmental and hydrological conditions, large-sample hydrological investigations are required in order to model reliable, robust and realistic approaches with potential for generality and transposability[190]. Therefore, it is imperative that large watershed dynamics are captured in future SWAT investigations for the different environmental, climatic and hydrological conditions found in Brazil, especially regarding expanded testing of the model in the Northeast, Central-West and North regions of Brazil (note Figure 3-7and Figure 3-8).

2) Risk Assessments & Disaster Management for Drought, Floods and Landslides: Droughts and floods represent the main impacts of extreme hydrometeorological situations in Brazil, affecting both populated areas and ecosystems[191,192]. The Brazilian Northeast suffers from recurrent droughts, which are often followed by floods[193], including a prolonged drought during 2010 to 2013 which was the worst drought in recent decades[194]. Droughts and floods are also part of the natural climate variability in the North Region of Brazil (Amazon), where the most intense droughts and floods in recent history have occurred in the last 10 years[192]. A recent drought in southeast Brazil (2014-2015) has resulted in the lowest observed river flows of the last 3 decades and water supply reservoirs for the São Paulo Metropolitan region having their dead volume being pumped[195-197]. Floods meanwhile represent 58% of the environmental disasters in Brazil[198]. These developments are consistent with the hypothesis that extreme droughts and floods have become more frequent and intense[199], and could amplify in the future[192]. Therefore, future hydrological modeling with SWAT in critical areas in Brazil combined with risk assessments, can lead to better preparedness and adaptation measures to reduce loss of life, property, crops, etc., and could lead to improvements in the sub-daily component of SWAT[200], the use of SWAT as a forecasting system for predicting the probability of floods and long-term probability of droughts, and other improvements.

3) Better Vegetation Representation (Parameters and Routines): Much of the typical natural vegetation represented by different Brazilian biomes (Figure 3-1) and many Brazilian crops are not currently included in the SWAT plant parameters database. Some studies have adapted or used other plant parameters already available in the database to represent different crops[e.g.,158]. According to a previous SWAT review study[10], there is a need to expand the plant parameter database to support a greater range of vegetation that can be simulated with the model and a need to perform more extensive testing of the crop components, including revisions to crop parameters where needed. This is further confirmed by the work performed for the Santa Maria/Torto watershed (Table 3-1)[130], which showed that the modified SWAT crop growth component more accurately replicated growth characteristics of tropical perennial vegetation and allowed for more flexibility in simulating leaf area index (LAI), which typically fluctuates less over different seasons compared to North American vegetation growth patterns.

4) Integration of Water Quality and Quantity Studies for Regulated Watersheds: Approximately 90% of Brazilian electricity consumption is met by hydropower plants[201]. River regulation by dams cause major impacts in the hydrology, river morphology, flow regimes, chemical and sediment transport, water quality and riverine/riparian ecosystems. There is a large number of reservoirs in Brazil and also new dams that are being built (e.g., Amazon River Basin; Figure 3-5). More in-depth studies are needed on the effects of reservoirs on the hydrology, sediment transport and water quality, and potential water allocation, which can improve overall knowledge of these processes and lead to improved reservoir representation in SWAT.

5) NWRP and Brazilian Forest Code: As noted previously, the Brazilian NWRP[1,2] has established bold sustainability, integrated management and safety objectives. Specific tools are available for implementing this policy such as: water resources plans, classification of water bodies in different "use classes", a permit system for water withdrawal and use, water pricing, and a water resources information system[1]. Recent changes in the Brazilian Forest Code (BFC)[202] policy, which was first created in 1965 and modified most recently in 2012, have generated considerable controversy and also have important water resources implications. The original BFC required conservation (Legal Reserve) of 80% of the native property area in the Amazon region and 20% in other biomes (Figure 3-1), and also designated Areas of Permanent Preservation (APPs) to preserve environmentally sensitive areas, which include riparian

preservation areas and hilltop preservation areas (high elevations and steep slopes). The new BFC maintains the Legal Reserve and riparian preservation area conservation requirements, and establishes new mechanisms that may result in enhanced provision of ecosystem services[202]. However, the revised BFC also reduces the hilltop preservation areas (reducing total area by 87%) and restoration requirements, and provides amnesty for pre-2008 illegal deforestations. Thus, there is an urgent need to use SWAT to evaluate the implications of adopting the NWRP and/or BFC for specific watersheds.

6) Watershed-Scale Water Quality studies: As previously described, the majority of surveyed Brazilian SWAT studies have focused on just hydrologic/streamflow analyses. Thus expanded water quality research of sediment, nutrient and other pollutant transport with SWAT is an important future research need, to better understand the implications and impacts of both point source and diffuse source pollution. This can potentially lead to better process understanding in different regions and conditions, even though detailed observed water quality data is scarce in some regions of Brazil. A broader SWAT water quality research emphasis will also support expanded scenario investigations such as evaluation of agricultural practices, determination of critical source areas and other possible water quality scenarios.

7) Land Use and Climate Change Scenarios and Impact Assessments: Brazil has experienced extensive land use changes and related impacts in recent decades, which could be further exacerbated as a result of future climate change, especially if more frequent extreme events occur as it has been predicted[199]. Therefore, simulating combined land use and climate change scenarios in SWAT can play an important role for better understanding the future implications of such changes, providing improved watershed and water resources management, and planning for a less vulnerable, more sustainable and adaptative future to better cope with these changes.

8) Bioenergy Crops Studies: At present, large areas of Brazil are devoted to short-rotation eucalyptus and sugar-cane crops for energy purposes[203], and production of biodiesel fuels from vegetable oils has also recently begun. Brazil is currently the largest producer, consumer and exporter of ethanol[204]. Eucalyptus wood is converted in charcoal for the Pig iron and Steel industry. Sugar cane is primarily used for ethanol production and has two key by-products:

bagasse, which is used for electricity production or the production of biodegradable plastic, and vinasse (stillage) which is mainly used for fertigation. Therefore, SWAT studies focused on hydrological and water quality impacts of bioernergy crops in Brazil are needed to assess the implications of the growing biofuel industry, which may benefit a range of different sectors.

9) Increased development of data resources in data scarce subregions: Multiple SWAT studies described challenges regarding obtaining adequate data, as discussed in Section 5. These SWAT application challenges continue to persist in many Brazilian regions due to data scarcity for setting up and calibrating/validating the model (especially for water quality assessments), resulting in the need to use more generic data and parametrizations. The development and maintenance of new data resources in data scarce areas would result in improved SWAT simulations and enhanced confidence regarding the predictions and quality of the studies.

10) Environmental Services/Ecossystem Services: The topic of environmental or ecosystem services, and its benefits for the society are a core component of modern social-ecological research[205], however its development and application in decision making is still a challenge[205,206]. SWAT and eco-hydrological modelling in general can provide much help on methodological terms for these applications.

11) Urban Management and Best Management Practices: Application of watershed models at urban scale and sub-daily time steps are very important for better understanding of flow and water quality dynamics. Recent developments in SWAT have been done to improve these studies and assessments, as sub-hourly flow models and algorithms for simulation of stormwater best management practices (BMPs). These recently developed facets of SWAT have to be better tested and explored[207].

3-7. Conclusions

The Brazilian biomes described here are characterized by megadiverse vegetation, climatic and hydrologic diversity, posing considerable challenges regarding the application of ecohydrological models such as SWAT. Nevertheless, the use of SWAT in Brazil has grown significantly in the recent years, as evidenced by the 113 studies (102 surveyed studies and 11 additional studies listed in Table 3-2. Selected recent studies published in English between 2012 and 2015 which reflect key SWAT application trends in Brazil) that were reviewed here. To date, the vast majority of the reported studies have focused only on hydrologic applications, with a smaller percentage reporting sediment transport results and only a few that report other pollutant (nutrients, pesticides, etc.) impacts. Over 60% of the previously published SWAT studies were conducted in the South or Southeast region of Brazil although use of the model is gradually expanding to other regions of the country. The studies found were mainly of an academic nature, revealing that considerable gaps remain regarding the use of SWAT as a decision support tool by environmental and hydrological government institutions and watershed committees.

The literature reviewed in this study indicates that the adoption and adaptation of SWAT to these diverse Brazilian environmental and climatic conditions is definitely promising, even for some watersheds which lack desired amounts of input and monitoring data. Of the 102 Brazilian SWAT studies that were surveyed between 1999 and 2013, 65% of them presented calibration and/or validation streamflow NSE statistics with the following results: (1) 94% of the monthly NSE values > 0.5 (considered satisfactory[149]), (2) 90% of the monthly NSE values were classified as “good” and “very good” per additional suggested criteria[160], and (3) roughly 75% of the daily NSE statistics > 0.5 (again satisfactory[160]). Similar statistical results were noted for daily streamflow NSE values reported for a smaller subset of Brazilian SWAT studies recently published in English. These overall hydrological statistical results are similar to recent trends reported in the existing SWAT literature[12-14]. The statistical outcomes reported for a limited number of studies that reported sediment testing results were more mixed, with some studies reporting satisfactory estimates while others reported results that were very poor.

In spite of reported successes with SWAT, extensive problems remain which must be addressed in order for the model to function as a fully robust simulation tool for Brazilian conditions. Many authors discussed data availability issues and recommended that the number of gauge stations in respective study watersheds and that collection of more input data in general be increased, and that easier platforms to access Brazilian data be created. In addition, even successful SWAT modeling applications may be masking significant underlying problems such as inadequate representation of crop characteristics or other inputs, inaccurate simulation of tropical perennial vegetation as described for the Santa Maria/Torto watershed study[130], or sediment transport phenomena that can't be captured by current standard SWAT codes[121]. Extensive additional testing of the model is needed, especially for water quality assessments, at a range of watershed scales including for large river basin systems. There is also a need to expand SWAT scenario-focused simulations that provide evaluations of critical Brazilian issues and/or legislation such as risk assessments for drought and floods, assessments of the effects of the NWRP and BFC, and scenario analyses of current and expanded bioenergy crop production or combined land use change and climate change studies.

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3-9-. References

1. Porto M. The Brazilian Water Law: A New Level of Participation and Decision Making. International Journal of Water Resources Development. 1998, 14(2); 175-182. doi: 10.1080/07900629849385.
2. Veiga LBE, Magrini A. The Brazilian Water Resources Management Policy: Fifteen years of success and challenges. Water Resour Manage. 2013; 27: 2287–2302. doi: 10.1007/s11269-013-0288-1.
3. Global Water Partnership. Technical Advisory Committee (TAC) Background Papers. Integrated Water Resources Management. Denmark: Global Water Partnership (TAC) TAC; 2000. 1403-5324 Contract No.: 4.
4. Global Water Partnership. Technical Advisory Committee (TAC) Background Papers. Solanes, M., Gonzalez-Villarreal, F. The Dublin Principles for Water as Reflected in a Comparative Assessment of Institutional and Legal Arrangements for Integrated WaterResources Management. Sweden: Global Water Partnership/Swedish International Development Cooperation Agency; 1999. 1403-5324 Contract No.: 3.

5. Daniel EB, Camp JV, LeBoeuf EJ, Penrod JR, Dobbins JP, Abkowitz MD. Watershed modeling and its applications: A state-of-the-art review. The Open Hydrol J. 2011; 5: 26-50. doi: 10.2174/1874378101105010026.

6. Borah DK, Bera M. Watershed-scale hydrologic and nonpoint-source pollution models: review of applications. Trans ASAE. 2004; 47(3): 789-803. doi: 10.13031/2013.16110.

7. Singh VP, Woolhiser DA. Mathematical modeling of watershed hydrology. J Hydrol Eng. 2002; 7(4): 270-292. doi: 10.1061/(ASCE)1084-0699(2002)7:4(270).

8. Arnold JG, Srinivasan R, Muttiah RS, Williams JR. Large area hydrologic modeling and assessment part I: Model development. Journal of the American Water Resources Association. 1998; 34(1): 73‐89. doi: 10.1111/j.1752-1688.1998.tb05961.x.

9. Arnold JG, Fohrer N. SWAT2000: current capabilities and research opportunities in applied watershed modeling. Hydrol Process. 2005; 19(3): 563-572. doi: 10.1002/hyp.5611.

10. Williams JR, Arnold JG, Kiniry JR, Gassman PW, Green CH. History of model development at Temple, Texas. Hydrol Sci J. 2008; 53(5): 948-960. doi: 10.1623/hysj.53.5.948.

11. Gassman PW, Reyes M, Green C, Arnold JG. The soil and water assessment tool: Historical development, applications, and future research directions. Trans ASABE. 2007; 50(4):1211-50.

12. Douglas-Mankin KR, Srinivasan R, Arnold JG. Soil and Water Assessment Tool (SWAT) model: Current developments and applications. Trans ASABE. 2010; 53(5): 1423-1431. Doi: 10.13031/2013.34915.

13. Tuppad P, Douglas-Mankin KR, Lee T, Srinivasan R, Arnold JG. Soil and Water Assessment Tool (SWAT) hydrologic/water quality model: Extended capability and wider adoption. Trans ASABE. 2011; 54(5): 1677-1684. doi: 10.13031/2013.34915.

14. Gassman, PW, Sadeghi AM, Srinivasan R. Applications of the SWAT Model Special Section: Overview and Insights. J Environ Qual. 2014; 43(1): 1-8. doi: 10.2134/jeq2013.11.0466.

15. Oliveira MQC, Medeiros YDP. Aplicação do modelo SWAT na avaliação de impactos decorrentes da modificação no uso do solo em bacias hidrográficas. XIII Simpósio Brasileiro de Recursos Hídricos; Belo Horizonte – MG. Brasil: ABRH; 1999.

16. Garbossa LHP, Vasconcelos LRC, Lapa KR, Blainski E, Pinheiro A. The use and results of the Soil and Water Assessment Tool in Brazil: A review from 1999 until 2010. 2011 International SWAT Conference; Toledo, Spain. 2011.

17. CIA. The World Factbook. Central Intelligence Agency, Washington, D.C. Available: https://www.cia.gov/library/publications/the-world-factbook/rankorder/2119rank. html?countryname=Brazil&countrycode=br&regionCode=soa&rank=6#br. Accessed [2015-01-24].

18. Mittermeier RA, Mittermeier CG. Megadiversity: Earth's biologically wealthiest nations. CEMEX, S A, 1997. Toronto, Ontario: Quebecor Printing, Inc.

19. Malhi Y, Roberts JT, Betts RA, Killeen, TJ, Li W, Nobre CA. Climate change, deforestation, and the fate of the Amazon. Science 2008; 319(5860): 169-172. doi: 10.1126/science.1146961.

20. Heckenberger, MJ, Russell JC, Toney JR, Schmidt MJ. The legacy of cultural landscapes in the Brazilian Amazon: implications for biodiversity. Phil. Trans. R. Soc. B 2007; 362: 197–208. doi: 10.1098/rstb.2006.1979.

21. Leal IR, Da Silva JM C, Tabarelli M, Lacher Jr. TE. Changing the course of biodiversity conservation in the Caatinga of Northeastern Brazil. Conservation Biology 2005; 19(3): 701-706. doi:10.1111/j.1523-1739.2005.00703.x.

22. Da Silva JM C, Bates JM. Biogeograhic patterns and conservation in the South American Cerrado: A tropical savanna hotspot. BioScience 2002; 52(3): 225-233. doi: 10.1641/0006-3568(2002)052[0225.

23. Silva JF, Fariñas MR, Felfili JM, Klink CA. Spatial heterogeneity, land use and conservation in the cerrado region of Brazil. Journal of Biogeography 2006; 33(3): 536-548. doi:10.1111/j.1365-2699.2005.01422.x.

24. Werneck FP. The diversification of eastern South American open vegetation biomes: Historical biogeography and perspectives. Quaternary Science Reviews 2011; 30(13-14): 1630-1648. doi:10.1016/j.quascirev.2011.03.009.

25. Junk WJ, da Cunha CN, Wantzen KM, Petermann P, Strüssmann C, Marques MI, et al. Biodiversity and its conservation in the Pantanal of Mato Grosso, Brazil. Aquatic Sciences 2006; 68: 278-309. doi:10.1007/s00027-006-0851-4.

26. Carnaval AC, Hickerson MJ, Haddad CFB, Rodrigues MT, Moritz C. Stability Predicts Genetic Diversity in the Brazilian Atlantic Forest Hotspot. Science 2009; 323(5915): 785-789. doi: 10.1126/science.1166955.

27. Overbeck GE, Müller SC, Fidelis A, Pfadenhauer J, Pillar VD, Blanco CC, et al. Brazil's neglected biome: The South Brazilian Campos. Perspectives in Plant Ecology, Evolution and Systematics 2007; 9(2): 101-116. doi: 10.1016/j.ppees.2007.07.005.

28. Myers N, Mittermeier RA, Mittermeier C G, da Fonseca GAB, Kent J. Biodiversity hotspots for conservation priorities. Nature 2000; 403: 853-858. doi:10.1038/35002501.

29. IBGE. Cartographer Mapa de Biomas. Instituto Brasileiro de Geografia e Estatística, IBGE; 2004. Available: http://www.ibge.gov.br/home/. Accessed [2015-01-26].

30. NIMER E. Climatologia do Brasil. Secretaria de Planejamento e Coordenação da Presidência da Republica and IBGE. Rio de Janeiro, 1989, 421p.

31. Quadro MFL, Machado LHR, Calbete S, Batista NNM, Sampaio G. Climatologia, Precipitação e Temperatura no período de 1986 a 1996. Revista Climanálise - Edição Comemorativa de 10 anos - CPTEC/INPE. 1996.

32. CPRM. Atlas Pluviométrico do Brasil, cartographer Mapa de Isoietas Anuais na escala 1:5.000.000. Serviço Geológico do Brasil, CPRM, 2010. Available: http://www.cprm.gov.br/publique/cgi/cgilua.exe/sys/start.htm?infoid=1351&sid=9. Accessed [2015-01-26].

33. IBGE. cartographer Mapa de Unidades Climáticas. Instituto Brasileiro de Geografia e Estatística, IBGE; 1997. Available: www.ibge.gov.br. Accessed [2015-01-26].

34. ANA. Conjuntura dos recursos hídricos no Brasil: informe 2011 (Agência Nacional de Águas). In: ANA, editor. Brasília-DF, Brazil: ANA; 2011. p. 112.

35. Manzatto CV, Freitas Junior E, Peres JRR (ed). Uso agrícola dos solos brasileiros. Rio de Janeiro: Embrapa Solos, 2002. 174 p. ISBN 85-85864-10-9.

36. Buol SW. Soils and agriculture in Central-West and North Brazil. Sci Agric. 2009: 66(5): 697-707. doi:10.1590/S0103-90162009000500016.

37. Lepsch IF. Status of soil surveys and demand for soil series descriptions in Brazil. Soil Horizons. 2013; 54(2): 1-5. doi:10.2136/sh2013-54-2-gc.

38. Guerra AJT, Fullen MA, Jorge MCO, Alexandre S T. Soil Erosion and Conservation in Brazil. Anuário do Instituto de Geociências. 2014: 37(1); 81-91. doi:10.11137/2014_1_81_91.

39. IBGE. Mapa de solos do Brasil. Rio de Janeiro, RJ, Brazil: Instituto Brasileiro de Geografia e Estatística (IGBE). Available: http://mapas.ibge.gov.br/tematicos/solos. Accessed [2015-05-05].

40. EMBRAPA - Empresa Brasileira de Pesquisa Agropecuária. Sistema Brasileiro de Classificação de Solos / Humberto Gonçalves dos Santos ... [et al.]. – 3 ed. rev. ampl. – Brasília, DF : Embrapa, 2013. 353 p. ISBN 978-85-7035-198-2.

41. Bendetti MM, Curi N, Sparovek G, Carvalho Filho A, Silva SHG. Updated Brazilian georeferenced soil database – An improvement for international scientific information exchanging. In Gungor B E O, ed. Principles, Application and Assessment in Soil Science. Rijeka, Croatia: InTech. 2011. pp. 309-332.

42. Garrido JM. Aplicação de modelo matemático de simulação com utilização de SIG à bacia do rio Jiquiriçá – Bahia. Brasília, Distrito Federal, Brasil: Universidade de Brasília; 2003.

43. Machado RE, Vettorazzi CA. Simulação da produção de sedimento para a microbacia hidrográfica do ribeirão Marins (SP). Revista Brasileira de Ciências do Solo. 2003;27:735-41.

44. Machado RE, Vettorazzi CA, Cruciani DE. Simulação de escoamento em uma Microbacia Hidrográfica Utilizando Técnicas de Modelagem e Geoprocessamento. Revista Brasileira de Recursos Hídricos. 2003;8(1):147-55.

45. Barsanti P, Disperati L, Marri P, Mione A. Soil erosion evaluation and multitemporal analysis in two Brazilian basins. 2nd International SWAT Conference; Bari, Italy. 2003.

46. Silva FGB, Minoti RT, Reis JAT, Tsuhako EM, Angelotti Netto A, Cestana S. Simulação da produção de sedimentos em uma sub-bacia hidrográfica experimental com o modelo SWAT. VI Encontro Nacional de Engenharia de Sedimentos; Vitória – ES, Brazil: ABRH; 2004.

47. Minoti RT, Silva FGB, Angelotti Netto A, Machado RE, Tsuhako EM, Cestana S. Determinação preliminar do aporte de sedimentos na microbacia do ribeirão Guabirobas (Estado de SP). VI Encontro Nacional de Engenharia de Sedimentos; Vitória– Espírito Santo, Brazil: ABRH; 2004.

48. UFBA. Gerenciamento dos recursos hídricos do semi-árido do estado da Bahia: Volume II – Subprojeto enquadramento de rio intermitente – estudo de caso do rio Salitre. Salvador-BA, Brazil: UFBA-Universidade Federal da Bahia, Departamento de Engenharia Ambiental, 2004.

49. Silva FGB, Neves FF, Crestana S. Avaliação da perda de solo em sub-bacias hidrográficas da região de Descalvado-SP a partir do modelo AVSWAT. XVI Simpósio Brasileiro de Recursos Hídricos; João Pessoa – Paraíba, Brazil: ABRH; 2005.

50. Neves FF, Silva FGB, Crestana S. Comparação entre três métodos de evapotranspiração potencial aplicados a duas sub-bacias hidrográficas de Descalvado – SP. XVI Simpósio Brasileiro de Recursos Hídricos; João Pessoa–Paraíba, Brazil: ABRH; 2005.
51. Gerhard P. Comunidades de peixes de riachos em função da paisagem da bacia do Rio Corumbataí, Estado de São Paulo. Piracicaba-SP, Brazil: Universidade de São Paulo (USP); 2005.
52. Baldissera GC. Aplicabilidade do modelo de simulação hidrológica SWAT (Soil and Water Assessment Tool), para a bacia hidrográfica do Rio Cuiabá/MT. Cuiabá-MT, Brazil: Universidade Federal do Mato Grosso; 2005.
53. Pereira JMG, Eid NJ, Campana NA. Aplicação de modelo matemático complexo de simulação com base em dados disponíveis. XVI Simpósio Brasileiro de Recursos Hídricos; João Pessoa–Paraíba, Brazil.: ABRH; 2005a.
54. Pereira JMG, Campana NA, Eid NJ. Processamento de dados para utilização de modelo matemático de simulação à bacia do rio Jiquiriçá - Bahia. XVI Simpósio Brasileiro de Recursos Hídricos; João Pessoa–Paraíba, Brazil.: ABRH; 2005b
55. Prado TBG, Moraes JFL, Adami SF. Evolução do uso das terras e produção de sedimentos na bacia hidrográfica do rio Jundiaí-Mirim. XVI Simpósio Brasileiro de Recursos Hídricos; João Pessoa–Paraíba, Brazil.: ABRH; 2005.
56. Coelho ACP, Hardt LPA, Fernandes CVS. Agregação de novas variáveis ao processo de planejamento urbano e regional sob a perspectiva de gestão dos recursos hídricos. XVI Simpósio Brasileiro de Recursos Hídricos; João Pessoa–PB, Brazil: ABRH; 2005.
57. Oliveira RC, Oliveira MQC, Medeiros YDP. Aplicação do modelo SWAT em região semi-árida. XVI Simpósio Brasileiro de Recursos Hídricos; João Pessoa–PB, Brazil.: ABRH; 2005a.
58. Oliveira MQC, Oliveira RC, Medeiros YDP. Hydrologic Modeling of a Semi-Arid Region in Brazil. 3rd International SWAT Conference; Duebendorf, Switzerland. 2005b.
59. Silva FGB, Neves FF, Crestana S. Simulação de parâmetros de qualidade de água em bacias hidrográficas com o uso do modelo AVSWAT. VIII Simpósio Ítalo-Brasileiro de Engenharia Sanitária e Ambiental; Fortaleza – CE, Brazil: ABES; 2006a.
60. Silva FGB, Pioltine V, Minotti RT, Crestana S, Dupas FA. Estimativa preliminar de perda de solo com o uso do modelo AVSWAT para bacias da região de Luís Antônio – S.P. VII Encontro Nacional de Engenharia de Sedimentos; Porto Alegre – RS, Brazil: ABRH; 2006b.
61. Neves FF, B. SFG, Crestana S. Uso do modelo AVSWAT na avaliação do aporte de nitrogênio (N) e fósforo (P) aos mananciais de uma microbacia hidrográfica contendo atividade avícola. Engenharia Sanitária e Ambiental. 2006;11(4):311-7.
62. Armas ED. Biogeodinâmica de herbicidas utilizados em cana-de-açúcar (Saccharum spp.) na sub-bacia do rio Corumbataí. Piracicaba-São Paulo, Brazil: Universidade de São Paulo (USP); 2006.
63. Garcia GJ, Gamero HG, Garcia LBR, Vettorazzi CA, Kröenert R, Volk M, et al. Impact of land use on soil erosion and on the water balance and water quality in the Corumbataí Watershed - SP. HOLOS Environment. 2006;6(2):118-36.
64. Moro M, Cruciani DE, Vettorazzi CA, Machado RE. Aplicação do modelo SWAT para simulação da produção de sedimentos em uma microbacia hidrográfica em cenários alternativos de uso do solo. VII Encontro Nacional de Engenharia de Sedimentos; Porto Alegre – S, Brazil: ABRH; 2006.

65. Paiva RCD, Paiva EMCD. Simulação hidrológica com modelo SWAT na Bacia Menino Deus I, representativa da Mata Atlântica. I Simpósio de Recursos Hídricos do Sul-Sudeste; Curitiba – PR, Brazil. 2006.
66. Bittencourt S, Gobbi EF. Carga máxima de fósforo admissível ao reservatório Piraquara II, uma aplicação do processo TMDL. Revista Brasileira de Ciências do Solo. 2006;30:595-603.
67. Rodrigues DF, Reis RS. Aplicação do modelo SWAT na estimativa da produção de sedimentos na bacia hidrográfica do rio Coruripe / AL. XVII Simpósio Brasileiro de Recursos Hídricos; São Paulo – SP, Brazil: ABRH; 2007.
68. Machado RE, Xavier AC, Cruciani DE, Vettorazzi CA. Efeito do nível de subdivisão em uma bacia hidrográfica na simulação da produção de sedimentos. Revista Brasileira de Recursos Hídricos. 2007;12(4):49-58.
69. Roloff G, Bley Jr C, Souza MLP. Modelo SWAT: Potencial de uso como auxiliar na gestão de pequenas bacias hidrográficas sem dados históricos. XVII Simpósio Brasileiro de Recursos Hídricos; São Paulo – SP, Brazil: ABRH; 2007.
70. Adriolo MV, Santos I, Gibertoni RC, Camargo ASG. Calibração do modelo SWAT para a produção e transporte de sedimentos. VI Simpósio Brasileiro sobre Pequenas e Médias Centrais Hidrelétricas; Belo Horizonte – MG, Brazil.2008.
71. Blainski E, Silveira FA, Conceição G. Utilização do modelo hidrológico SWAT para estudos na microbacia hidrográfica do rio Araranguá/SC. Taller Internacional Red Riegos - CYTED; Florianópolis-SC, Brazil. 2008.
72. Lopes NHY, Godoy FB, Kobiyama M. Análise da produção de água e de sedimento em uma microbacia experimental com a aplicação do modelo SWAT. VI Simpósio de Engenharia Ambiental; Serra Negra – SP, Brazil. 2008.
73. Lopes NHY, Kobiyama M. Análise da produção de sedimentos e da qualidade da água em uma microbacia experimental com SWAT. VIII Encontro Nacional de Engenharia de Sedimentos; Campo Grande – MS, Brazil. 2008.
74. Lopes NHY, Kobiyama M. Análise do equilíbrio hidrossedimentológico em uma microbacia experimental com o modelo SWAT e as características geomorfológicas. VII Simpósio Nacional de Geomorfologia e II Encontro Latino-Americano de Geomorfologia; Belo Horizonte – MG, Brazil.2008.
75. Marchioro E. Modelagem hidrossedimentológica na bacia do córrego Santa Maria: Subsídios à aplicação de práticas de conservação de água e solo no noroeste fluminense. Rio de Janeiro - RJ, Brazil: Universidade Federal do Rio de Janeiro (UFRJ); 2008.
76. Junqueira CAR, Silva RS. Avaliação ambiental aplicável a bacias hidrográficas no meio urbano: Análise dos métodos Amorim & Cordeiro, PESMU e SWAT. Revista de Estudos Ambientais. 2008 10(2):6-23.
77. Malutta S, Kobiyama M, Corseuil CW. Aplicação do modelo SWAT no gerenciamento de bacias hidrográficas: Bacias-escola na região norte catarinense. Encontro Nacional dos Estudantes de Engenharia Ambiental; Viçosa- MG, Brazil: Universidade Federal de Viçosa (UFV); 2009.
78. Souza RM, Santos I, Kobiyama M. O modelo SWAT como ferramenta para a gestão de recursos hídricos: avaliação de vazões de outorga na bacia hidrográfica do Altíssimo Rio Negro. In: ABRH, editor. XVIII Simpósio Brasileiro de Recursos Hídricos; Campo Grande – MS, Brazil. 2009.

79. Gibertoni RFC, Santos I, Müller II, Pereira PS. Modelagem da produção e transporte de sedimentos em bacias hidrográficas do litoral paranaense: o caso da bacia do rio Nhundiaquara. XVIII Simpósio Brasileiro de Recursos Hídricos; Campo Grande – MS, Brazil.: ABRH; 2009.
80. Blainski E, Garbossa LHP. Estimativa do regime hidrológico em uma bacia hidrográfica com base na modelagem hidrológica dinâmica e distribuída. XVIII Simpósio Brasileiro de Recursos Hídricos; Campo Grande – MS, Brazil: ABRH; 2009.
81. Uzeika T. Aplicabilidade do modelo SWAT (Soil and Water Assessment Tool) na simulação da produção de sedimentos em uma pequena bacia hidrográfica rural. Porto Alegre- RS, Brazil: Universidade Federal do Rio Grande do Sul; 2009.
82. Lubitz E. Avaliação da aplicação do modelo hidrológico SWAT à bacia do ribeirão Concórdia – Lontras. Blumenau- SC, Brazil: Universidade Regional de Blumenau; 2009.
83. Lino JFL, Corseuil CW, Kobiyama M, Malutta S, Uda K, Bortolotto NL, et al. Análise da vazão da bacia hidrográfica do rio Preto com o modelo SWAT. In XVIII Simpósio Brasileiro de Recursos Hídricos; Campo Grande – MS, Brazil: ABRH; 2009.
84. Paim JB, Menezes JT. Estimativa do balanço sedimentar da bacia do rio Tijucas (SC-Brasil) a partir da aplicação do modelo hidrológico SWAT. Revista Geográfica Acadêmica. 2009;3(2):5-14.
85. Mercuri EGF, Deppe F, Lohmann M, Simões K. Metodologia da geração de dados de entrada e aplicação do modelo SWAT para bacias hidrográficas brasileiras. XIV Simpósio Brasileiro de Sensoriamento Remoto; Natal – Rio Grande do Norte, Brazil. 2009.
86. Tesch F, Caiado MAC. Avaliação de modelos de poluição difusa para verificação de eficácia da aplicação do código florestal na melhoria da qualidade da água de bacias hidrográficas. IV Jornada de Iniciação Científica do Ifes and II Jornada de Iniciação em Desenvolvimento Tecnológico e Inovação do Ifes; Vitória –ES, Brazil. 2009.
87. Souza RM, Santos I. Regionalização de vazões mínimas na bacia hidrográfica do Altíssimo Rio Negro, Região Sul-Brasileira, com a aplicação do modelo SWAT. V SimpGEO - Simpósio Paranaense de Pós-Graduação e Pesquisa em Geografia: Estado da Arte, tendências e desafios; PR, Brazil. 2010.
88. Schultz GB, Souza RM, Santos I. Simulação da produção e transporte de sedimentos na bacia do Altíssimo rio Negro com o modelo SWAT. IX Encontro Nacional de Engenharia de Sedimentos; Brasília – DF, Brazil. 2010.
89. Santos I, Andriolo MV, Gibertoni RC, Kobiyama M. Use of the SWAT model to evaluate the impact of different land use scenarios on discharge and sediment transport in the Apucaraninha River watershed, southern Brazil. Symposium of the International Commission on Continental Erosion – Sediment Dynamics for a Changing Future; Warsaw, Poland. 2010.
90. Blainski E, Garbossa LHP, Malutta S. Aplicação do modelo hidrológico SWAT (Soil Water Assessment Tool) para a simulação da perda de solo e da disponibilidade hídrica em uma bacia hidrográfica não instrumentada. X Simpósio de Recursos Hídricos do Nordeste; Fortaleza – CE, Brazil: ABRH; 2010.
91. Bonumá NB, Reichert JM, Minella JP, Dalbianco L, Rodrigues MF, Barros CAPd. Análise de sensibilidade dos parâmetros do modelo SWAT para simulação de escoamento e aporte de sedimentos em bacias hidrográficas. XVIII Reunião Brasileira de Manejo e Conservação do Solo e da Água; Teresina - PI, Brazil. 2010.

92. Bonumá NB, Reichert JM, Minella JP, Barros CAP, Rodrigues MF, Buarque DC. Balanço hídrico e sua relação com a modelagem da produção de sedimentos em uma pequena bacia hidrográfica rural. IX Encontro Nacional de Engenharia de Sedimentos; Brasília – DF, Brazil. 2010.
93. Bonumá NB, Reichert JM, Jacomet L, Oliveira A, Rodrigues MF, Minella JPG. Simulação da produção de sedimentos em uma pequena bacia hidrográfica rural no sul do Brasil. XXXII Congresso Brasileiro de Ciência do Solo; Fortaleza- CE, Brazil. 2009.
94. Pereira JCD, Silva FGB, Dupas FA, Paes FS. Estudo de perda de solo na bacia hidrográfica do ribeirão da Cachoeirinha-MG, com a finalidade de obter estimativas aproximadas para o município de Santa Rita do Sapucaí-MG. IX Encontro Nacional de Engenharia de Sedimentos; Brasília – DF, Brazil. 2010.
95. Baltokoski V, Tavares MHF, Machado RE, Oliveira MP. Calibração de modelo para a simulação de vazão e de fósforo total nas sub-bacias dos rios Conrado e Pinheiro – Pato Branco (PR). Revista Brasileira de Ciência do Solo. 2010; 34:253-61.
96. Trindade PBCB, Coutinho LFN, Caiado MAC, Heatwole CD. Evaluation of nutrient modeling by SWAT under tropical conditions. 21st Century Watershed Technology: Improving Water Quality and Environment Conference Universidad EARTH, Costa Rica. 2010.
97. Fontes AS, Oliveira MQC, Medeiros YDP. Calibração do modelo SWAT em bacias do semi-árido com auxílio da hidrologia isotópica. X Simpósio de Recursos Hídricos do Nordeste; Fortaleza – CE, Brazil.: ABRH; 2010.
98. Garbossa LHP, Blainski E, Justen JGK, Vasconcelos LR. Potencial de uso de modelo hidrológico de base física na avaliação da legislação florestal e seus impactos nos cenários hidrológicos. X Simpósio de Recursos Hídricos do Nordeste; Fortaleza – CE, Brazil.: ABRH; 2010.
99. Blainski E, Araujo IS, Mello MF, Borges RC. Sistema de monitoramento e previsão hidrológica do Rio Araranguá- SC. XIX Simpósio Brasileiro de Recursos Hídricos; Maceió – AL, Brazil. 2011.
100. Santos RdO. Avaliação da Produção de sedimentos na bacia hidrográfica do Rio Potengi através do modelo SWAT. Natal- RN, Brazil: Universidade Federal do Rio Grande do Norte; 2010.
101. Carvalho Neto JG, Lunguinho RL, Srinivasan VS, Rufino IAA, Taveira IMLM. A influência dos métodos da interpolação na geração dos modelos numéricos de terreno e os resultados da simulação pelo modelo SWAT. IX Encontro Nacional de Engenharia de Sedimentos; Brasília- DF, Brazil. 2010.
102. Lelis TA, Calijuri ML. Modelagem hidrossedimentológica de bacia hidrográfica na região sudeste do Brasil, utilizando o SWAT. Revista Ambiente & Água – An Interdisciplinary Journal of Applied Science. 2010 5(2):158-74.
103. Rocha EO, Calijuri ML, Carvalho IC, Santiago AF, Machado e Silva MDF. Utilização do modelo SWAT no monitoramento de impactos ambientais decorrentes de alterações climáticas. XXIV Congresso Brasileiro de Cartografia; Aracaju - SE, Brazil. 2010.
104. Sousa AML, Castro NMR, Kaufmann V, Vitorino MI. Estimativa dos fluxos de calor a partir de imagens orbitais para aplicação na modelização hidrológica. XVI Congresso Brasileiro de Meteorologia; Belém – PA, Brazil.2010.
105. Silva VA, Amorim RR, Santos MCF, Perez Filho A, Moreau MS. A utilização de técnicas de geoprocessamento para modelagem de cenários de uso e perda de solo na bacia hidrográfica do Rio Colônia no litoral sul da Bahia (BRASIL). VI Seminário Latino Americano de Geografia Física; II Seminário Ibero Americano de Geografia Física; Universidade de Coimbra. 2010.

106. Pinheiro-Jesus CF, Paim GF, Palma EG, Adorno EV, Duarte MCM, Santos MBC. Geoprocessamento: Instrumento para a Gestão dos Recursos Hídricos na Delimitação Automática Unidades Hidrográficas. XXIV Congresso Brasileiro de Cartografia; Aracaju- SE, Brazil. 2010.
107. Silva VA, Moreau MS, Moreau AMSS, Rego NAC. Uso da terra e perda de solo na Bacia Hidrográfica do Rio Colônia, BA. Revista Brasileira de Engenharia Agrícola e Ambiental. 2011;15(3):310-5.
108. Blainski E, Silveira FA, Conceição G, Garbossa LHP, Vianna LF. Estimated soil use impacts in the Araranguá river basin through the use of the hydrologic modeling technique. Agropecuária Catarinense. 2011;24(1):65-70.
109. Aguiar RO. Estudos de calibração do modelo AVSWAT em bacias hidrográficas do Sul de Minas Gerais, Serra da Mantiqueira. Itajubá- MG, Brazil: Universidade Federal de Itajubá - UNIFEI; 2011.
110. Ferrigo S. Utilização do modelo SWAT na estimativa de produção de sedimentos na bacia do Córrego Capão Comprido no Distrito Federal. Florianópolis- SC, Brazil: Universidade Federal de Santa Catarina (UFSC); 2011.
111. Bortolotto NL, Kobiyama M, Corseuil CW. Avaliação hidrossedimentológica da Bacia do Rio Cunha, município de Rio Cedros/SC, com o modelo SWAT. XIX Simpósio Brasileiro de Recursos Hídricos; Maceiá-AL, Brazil: ABRH; 2011.
112. Xavier FV, Oliveira SA, Silveira A. Aplicabilidade do modelo hidrossedimentológico AVSWAT na Simulação do transporte de sedimentos, na Bacia Hidrográfica do Rio Manso - Mato Grosso, Brasil. XIX Simpósio Brasileiro de Recursos Hídricos; Maceió-AL, Brazil: ABRH; 2011.
113. Malutta S, Kobiyama M. SWAT application to analyze the floods in Negrinho River basin – SC, Brazil. 12th International Conference on Urban Drainage, Porto Alegre-RS, Brazil. 2011.
114. Galharte CA. Estimativa do escorrimento superficial e da produção de sedimentos em áreas de atividades agrossilvopastoris, no Estado de São Paulo, em função da mudança de uso e cobertura do solo. [tese] São Carlos-SP, Brazil: Universidade de São Paulo (USP); 2011.
115. Duraes MF, Mello CR, Naghettini M. Applicability of the SWAT model for hydrologic simulation in Paraopeba River Basin, MG. Cerne, Lavras. 2011; 17(4): 481-8.
116. Carvalho Neto JG, Srinivasan VS, Rufino IAA. Study of hypothetical scenarios in the Riacho dos Namorados Watershed in Cariri Paraibano using SWAT model. Rev Geogr Acadêmica. 2011; 5(2): 30-40.
117. Meira Neto AA, Fontes AS, Medeiros YDP. Aplicabilidade do modelo SWAT a um sistema hidrológico complexo de clima semi-árido. XIX Simpósio Brasileiro de Recursos Hídricos; Maceió-AL, Brazil: ABRH; 2011.
118. Carvalho Neto JG, Srinivasan VS, Rufino IA. Hydrosedimentological simulation, analyzing two DEM, of two small sub-basins in the Paraibano Cariri using the SWAT model. Rev Geogr Acadêmica. 2011b; 5(1): 48-58.
119. da Silva LRS. Análise de incerteza e avaliacâo dos fatores influentes no desempenho de modelos de simulacâo de bacias hidrográficas. Brasília, Brazil: Universidade de Brasília, Faculdade de Technologia, Departamento de Engenharia Civil e Ambiental, 2010.
120. Fernandes JG, Galvíncio JD, Freire MBGdS. O Modelo SWAT e suas Possibilidades de Aplicações em APL Agrícolas. Revista Brasileira de Geografia Física. 2012;01:115-26.

121. Bonumá N B, Rossi C G, Arnold J G, Reichert J M, Minella J P, Allen P M. Simulating Landscape Sediment Transport Capacity by Using a Modified SWAT Model. Journal of Environment Quality. 2014; 43(1): 55-66. doi:10.2134/jeq2012.0217.
122. Uzeika T, Merten GH, Minella JPG, Moro M. Use of the SWAT model for hydro-sedimentologic simulation in a small rural watershed. R Bras Ci Solo. 2012; 36.
123. Perazzoli M, Pinheiro A, Kaufmann V. Assessing the impact of climate change scenarios on water resources in southern Brazil. Hydrological Sciences Journal. 2013; 58(1):77-87.
124. Aragão Rd, Cruz MAS, Amorim JRAd, Mendonça LC, Figueiredo EEd, Srinivasan VS. Análise de sensibilidade dos parâmetros do modelo SWAT e simulação dos processos hidrossedimentológicos em uma bacia no agreste nordestino. R Bras Ci Solo. 2013;37:1091-102.
125. Secchin LF. Caracterização Ambiental e Estimativa da Produção de Cargas Difusas da Área de Drenagem da Represa de Itupararanga, SP. [tese] São Carlos-SP, Brazil: Universidade de São Paulo (USP); 2012.
126. Herrera DJM, Hernandez LCH. Aplicação do modelo SWAT para a calibração de vazões diárias na microbacia hidrográfica do córrego do Jerivá, Brasília DF. XI Simpósio de Recursos Hídricos do Nordeste; João Pessoa – PB, Brazil: ABRH; 2012.
127. Lessa LGF, Silva AFd, Zimback CRL, Machado RE. Análise Espacial do Conteúdo de Água da Bacia hidrográfica do Rio Pardo. Irriga, Botucatu. 2012; 17:376 - 86.
128. Strauch M, Bernhofer C, Koide S, Volk M, Lorz C, Makeschin F. Using precipitation data ensemble for uncertainty analysis in SWAT streamflow simulation. Journal of Hydrology. 2012;414-415:413-24.
129. Salles LdA. Calibração e validação do modelo SWAT para a predição de vazões na bacia do Ribeirão Pipiripau. Brasília-DF: Universidade de Brasília; 2012.
130. Strauch M, Volk M. SWAT plant growth modification for improved modeling of perennial vegetation in the tropics. Ecological Modelling. 2013;269:98-112.
131. Lelis TA, Calijuri ML, Santiago AdF, Lima DCd, Rocha EdO. Análise de sensibilidade e calibração do modelo SWAT aplicado em bacia hidrográfica da região Sudeste do Brasil. R Bras Ci Solo. 2012;36:623-34.
132. Taveira IMLdM, Srinivasan VS, Galvão CdO, Morais SDA, Silva MJM. Simulação hidrossedimentológica da bacia representativa de Sumé com o modelo SWAT. Simpósio de Recursos Hídricos do Nordeste; João Pessoa-PB, Brazil: ABRH; 2012, PAP012245.
133. Alcântara HM, Cunha JEBL, Galvão CdO, Taveira IMLdM, Srinivasan VS. Uso do modelo SWAT para estimativa da produção de sedimentos como um subsídio ao planejamento ambiental. Simpósio de Recursos Hídricos do Nordeste; João Pessoa-PB, Brazil: ABRH; 2012, PAP012245.
134. Andrade MA, Mello CRd, Beskow S. Simulação hidrológica em uma bacia hidrográfica representativa dos Latossolos na região Alto Rio Grande, MG. Revista Brasileira de Engenharia Agrícola e Ambiental. 2013;17(1):69-76.
135. Bonumá NB, Rossi CG, Arnold JG, Reichert JM , Paiva EMCD. Hydrology evaluation of the Soil and Water Assessment Tool considering measurement uncertainty for a small watershed in Southern Brazil. Appl. Eng. Agric. 2013; 29(2):189-200.
136. Xavier FV. Contribuições metodológicas ao estudo da produção e distribuição espacial de sedimentos na bacia hidrográfica do Rio Manso utilizando o modelo AVSWAT. Cuiabá, MT, Julho de 2009: Universidade Federal de Mato Grosso; 2009.

137. Paim JB. Avaliação do Potencial de Produção de Sedimentos na Bacia Hidrográfica do Rio Piçarras utilizando técnicas de modelagem e geoprocessamento. Itajaí-SC, Brazil: Universidade do Vale do Itajaí – UNIVALI; 2012.
138. Blainski E, Malutta S, Garbossa LHP. Simulação da perda de solo e do regime hidrológico na bacia hidrográfica do Lajeado dos Fragosos- SC. XXII Congreso Argentino de la Ciencia del Suelo - 31 de mayo al 4 de Junio de Rosario, Argentina. 2010.
139. Silva PGd. Simulação do fluxo hídrico e da produção de sedimento da bacia do Rio Araranguá, SC, a partir da aplicação do modelo hidrológico SWAT. Itajaí, Brazil: Universidade do Vale do Itajaí; 2010.
140. Malutta S, Kobiyama M, Fuerst L. Análise da qualidade de água dos principais rios do município de Rio Negrinho (SC) / Analysis of water quality of principal rivers in the Rio Negrinho city (SC). Revista Ambiência. 2013; 9(1):173-86.
141. Strauch M, Lima JEFW, Volk M, Lorz C, Makeschin F. The impact of Best Management Practices on simulated streamflow and sediment load in a Central Brazilian catchment. Journal of environmental management. 2013; 127 Suppl: S24-36.
142. ABRH reference: Associação Brasileira de Recursos Hídricos (ABRH). Porto Alegre - RS, Brazil. Available at: http://www.abrh.org.br/ [Dec. 22, 2014].
143. Pissarra TCT, Migliaccio KW, Arraes CL, Oliveira GS, Bueno CRP, Campos S. 2014. 2014 SWAT Conference Proceedings. Pernambuco, Brazil. http://swat.tamu.edu/media/ 114647/2014 -brazil-swat-conference-proceedings-secured.pdf [Jan. 07, 2014]
144. Oliveira GS, Costa BO, Pissarra TCT, Guidolini JF, Carneiro FM, Silva MC. 2014. Modelagem hidrológica na bacia hidrográfica Ribeirão Pádua Diniz, no noroeste de São Paulo, Brasil. 2014 SWAT Conference Proceedings. Pernambuco, Brazil. http://swat.tamu.edu /media/114647/ 2014-brazil-swat-conference-proceedings-secured.pdf [Jan. 07, 2014]
145. Oliveira GS, Guidolini JF, Passos AO, Carneiro FM, Costa BO, Silva MC, Pissarra TCT. 2014. Territorial planning in River Uberaba's Watershed, MG, Brazil. 2014 SWAT Conference Proceedings. Pernambuco, Brazil. http://swat.tamu.edu/media/114647/2014-brazil-swat-conference-proceedings-secured.pdf [Jan. 07, 2014]
146. SWAT (Soil & Water Assessment Tool) Website. 2014. http://swat.tamu.edu/ [Jan. 07, 2014]
147. SWAT 2014 Conference Book of Abstracts, Pernambuco, Brazil. 2014. http://swat.tamu.edu/media/99100/book-of-abstracts-final-2014-07-14.pdf [Jan. 07, 2014]
148. Shiklomanov IA. World Water Resources. A New Appraisal and Assessment for the 21st Century. UNESCO. Paris. 1999.
149. ANA. Agência Nacional de Águas. Região Hidrográfica Amazônica; A maior do mundo em disponibilidade de água. http://www2.ana.gov.br/Paginas/portais/bacias/amazonica.aspx. [Jan. 07, 2014]
150. Strauch, M, Volk M. 2014. Setting up SWAT for the Upper Amazon. *Book of Abstracts of the 2014 SWAT Conference*. http://swat.tamu.edu/media/99100/book-of-abstracts-final-2014-07-14.pdf [January 07, 2015].
151. Ribeiro, CBM, Mohanty BP, Bressiani DA, Fernandes JG, Rotunno Filho OCR. 2014. Parameterization of physical and climatic characteristics in the Amazon basin for hydrological simulation with SWAT model. *Book of Abstracts of the 2014 SWAT Conference*. http://swat.tamu.edu/media/99100/book-of-abstracts-final-2014-07-14.pdf [January 07, 2015].

152. Sanchez Perez JM, Sauvage S. 2014. The role of the alluvial floodplain to modeling water discharge using SWAT model in the Amazon catchment. *Book of Abstracts of the 2014 SWAT Conference*. http://swat.tamu.edu/media/99100/ book-of-abstracts-final-2014-07-14.pdf [January 07, 2015].
153. Creech C, Brito R, Selegean J, Miller C. 2014. Anthropogenic Impacts to the Sediment Budget of the São Francisco River Navigation Channel using SWAT. *Book of Abstracts of the 2014 SWAT Conference*. http://swat.tamu.edu/media/99100/book-of-abstracts-final-2014-07-14.pdf [January 07, 2015].
154. Creech, CT, Siqueira RB, Selegean S J, Miller C. Anthropogenic impacts to the sediment budget of the São Francisco River navigation channel using SWAT. Int J Agric Biol Eng. 2015. doi:10.3965/j.ijabe.20150803.
155. Koch H, Liersch S, Azevedo R, Silva A, Hattermann F. 2014. Modelling of water availability and water management for the São Francisco Basin, Brazil. *Book of Abstracts of the 2014 SWAT Conference*. http://swat.tamu.edu/media/99100/ book-of-abstracts-final-2014-07-14.pdf [January 07, 2015].
156. Fernandes J, Galvincio J, Srinivasan R, Freire MB. 2014. Use of the SWAT Model for Evaluation of Flow and Runoff in Hydroelectric Plant of Xingo. *Book of Abstracts of the 2014 SWAT Conference*. http://swat.tamu.edu/media/99100/book-of-abstracts-final-2014-07-14.pdf [January 07, 2015].
157. Bressiani DA, Srinivasan R, Jones CA, Mendiondo, EM. 2014. Climate change impacts on the streamflow of a semi-arid watershed, Northeast Brazil. *Book of Abstracts of the 2014 SWAT Conference*. http://swat.tamu.edu/media/99100/book-of-abstracts-final-2014-07-14.pdf [January 07, 2015].
158. Bressiani DA, Srinivasan R, Jones CA, Mendiondo EM. Effects of different spatial and temporal weather data resolutions on the streamflow modeling of a semi-arid basin, Northeast Brazil. Int J Agric Biol Eng. 2015. doi:10.3965/j.ijabe.20150803.970.
159. Nash JE, Sutcliffe, JV. River flow forecasting through conceptual models: Part 1. A discussion of principles. *J. Hydrology*; 1970; 10(3): 282-290.
160. Moriasi DN, Arnold JG, Liew MWV, Bingner RL, Harmel RD, Veith TL. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE. 2007; 50(3): 885−900. doi:10.13031/2013.23153.
161. Rodrigues DBB, Gupta HV, Mendiondo EM. A blue/green water-based accounting framework for assessment of water security. Water Resour. Res. 2014. 50, 7187–7205. doi:10.1002/2013WR014274.
162. Tobin K, Bennet M. Satellite precipitation products and hydrologic applications. Water International. 2014. 39(3); 360-380. doi:10.1080/02508060.2013.870423.
163. Rocha EO, Calijuri ML, Santiago AF, de Assis LC, Alves LGS. The Contribution of Conservation Practices in Reducing Runoff, Soil Loss, and Transport of Nutrients at the Watershed Level. Water Resources Management; 2012. 26(13): 3831-3852. doi: 10.1007/s11269-012-0106-1.
164. Pereira DR, de Almeida AQ, Martinez MA, Rosa DRQ. Impacts of deforestation on water balance components of a watershed on the Brazilian East Coast. Revista Brasileira de Ciência do Solo. 2014. 38; 1350-1358. doi:10.1590/S0100-06832014000400030.
165. Rodrigues EL, Elmiro MA T, Braga FA, Jacobi CM, Rossi RD. Impact of changes in land use in the flow of the Pará River Basin, MG. Revista Brasileira de Engenharia Agricola e Ambiental. 2014. 19(1); 70-76. doi: 10.1590/1807-1929/agriambi.v19n1p70-76.

166. Pereira DR, Martinez MA, de Almeida AQ, Pruski FF, da Silva DD, Zonta JH. Hydrological simulation using SWAT model in headwater basin in Southeast Brazil. Engenharia Agrícola Jaboticabal. 2014. 34(4); 789-799. doi: 10.1590/S0100-69162014000400018.
167. Fukunaga DC, Cecilio RA, Zanetti S, Oliveira LT, Caiado MAC. Application of the SWAT hydrologic model to a tropical watershed at Brazil. Catena. 2015; 125: 206-213. doi:10.1016/j.catena.2014.10.032.
168. de Silva RM, Santos CAG, Silva VCL, Silva LP. Erosivity, surface runoff, and soil erosion estimation using GIS-coupled runoff-erosion model in the Mamuaba catchment, Brazil. 2013. 185(11); 8977-8990. doi:10.1007/s10661-013-3228-x.
169. Pinto DBF, da Silva AM, Beskow S, de Mello CR, Coelho G. Application of the Soil and Water Assessment Tool (SWAT) for sediment transport simulation at a headwater watershed in Minas Gerais state, Brazil. 2013. 56(2); 697-709. doi: 10.13031/2013.42668.
170. Huffman GJ, Adler RF, Bolvin DT, Gu G, Nelkin EJ, Bowman, K, et al. The TRMM Multi-satellite Precipitation Analysis (TMPA): Quasi-global, multi-year, combined-sensor precipitation estimates at fine scales. J. Hydrometeor. 2007; 8: 38–55. doi:10.1175/JHM560.1.
171. Fuka, DR, Walter MT, MacAllister CA, Degaetano AT, Steenhuis T S, Easton, Z M. Using the Climate Forecast System Reanalysis dataset to improve weather input data for watershed models. Hydrol. Proc. 2013; 28(22): 5613–562. Doi: 10.1002/hyp.10073.
172. Texas A&M AgriLife Research. Global Weather Data for SWAT. College Station, TX: Texas A&M University 2015. Available: http://globalweather.tamu.edu/. Accessed on: [2015-03-21].
173. Arnold JG, Allen PM, Volk M, Williams JR, Bosch D. Assessment of different representations of spatial variability on SWAT model performance. Transactions of the ASABE. 2010; 53(5): 1433-1443. doi:10.13031/2013.34913.
174. Bosch DD, Arnold JG, Volk M, Allen PM. Simulation of a low-gradient coastal plain watershed using the SWAT landscape model. Transactions of the ASABE. 2010; 53(5): 1445-1456. doi:10.13031/2013.34899.
175. Falkenmark M, Rockstrom J. The new blue and green water paradigm: Breaking new ground for water resources planning and management. J. Water Resour. Plann. Manage. 2006; 132(3): 129–132. doi:10.1061/(ASCE)0733-9496(2006)132:3(129).
176. IPCC. 4.4.2.2. A2 Scenarios; 4.4.2.4. B2 Scenarios. In: Nakicenovic N., Swart R. (Ed.). Emissions Scenarios. Cambridge, United Kingdom: Cambridge University Press. 2000. Available: http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=89 [Accessed on 2015-03-25].
177. SWAT. ArcSWAT: ArcGIS-ArcView extension and graphical user input interface for SWAT. Temple, Texas: U.S. Department of Agriculture, Agricultural Research Service, Grassland, Soil & Water Research Laboratory. 2015. Available: http://swat.tamu.edu/ software/arcswat/. Accessed on [2015-03-27].
178. IGBE. Atlas Nacional do Brasil. Rio de Janeiro, RJ, Brazil: Instituto Brasileiro de Geografia e Estatística (IGBE). 2010. Available: ftp://geoftp.ibge.gov.br/atlas/atlas _nacional_do_brasil_2010 /. Accessed [2015-05-08].
179. BDGEx. Banco de Dado Geográphicos do Exército: Versão 3.1. Available: http://www.geoportal.eb.mil.br/mediador/. Accessed [2015-05-08].
180. Governo Federal Brasil. Acesso à Informação. 2015. Available: http://www.acessoainformacao.gov.br/. Accessed on [2015-03-31].

181. Codeplan. Mapas Topográficos Plani-altimétricos Digitais do Distrito Federal na escala de 1:10.000, Brasília. 1992.

182. INPE - Instituto Nacional de Pesquisas Espaciais. Mapa de uso e cobertura da terra do território brasileiro para uso em modelagem climática e meteorológica. Relatório de Pesquisa. INPE. São José dos Campos, 2013. Available: http://urlib.net/8JMKD3MGP7W/3ECULQ5. Accessed on: [2015-03-21].

183. Vieira RMS P V, Cunha APMA, Alvalá RCS, Carvalho VC, Ferraz Neto S; Sestini M F. Land use and land cover map of a semiarid region of Brazil for meteorological and climatic models. Rev. Bras. Meteorol. São Paulo, 2013; 28 (2). Available: <http://www.scielo.br/ scielo.php?script=sci_ arttext&pid=S0102-77862013000200002&lng =en&nrm=iso> Accessed on: [2015-03-21]. Doi: 10.1590/S0102-77862013000200002.

184. GEOAMBIENTE Sensoriamento Remoto Ltda. Projeto de proteção da mata atlântica em Santa Catarina (PPMA / SC). Relatório Técnico do Mapeamento Temático Geral do Estado de SC. São José dos Campos – SP. 2008; 90p.

185. SAR. Secretaria de Agricultura e Abastecimento do Estado de Santa Catarina. Inventário Florístico Florestal de Santa Catarina. Relatório do Projeto Piloto. Florianópolis. 2005; 170p.

186. CONSÓRCIO PARANASAN - ENGEVIX-CKC-ETC-BVIETEP-ESTEIO-RDR. Estudo de impacto ambiental - Barragem Piraquara II. Curitiba, Projeto de Saneamento Ambiental do Paraná – PARANÁSAN/UGP PARANÁSAN –SANEPAR, 2000; 3.

187. BRASIL. Programa Produtor de Água e Relatório de Diagnóstico Socioambiental da Bacia do Ribeirão Pipiripau, 2010. Brasília, DF, p. 59.

188. Reatto A, Martins É S, Farias M FR, da Silva A V, de Carvalho Jr, O A. Mapa Pedológico Digital – SIG Atualizado do Distrito Federal Escala 1:100.000 e uma Síntese do Texto Explicativo. 2004. Planaltina, DF, p. 31.

189. Ministério do Meio Ambiente, dos Recursos Hídricos e da Amazonia Legal. Plano de Conservação da Bacia do Alto Paraguay (PCBAP) Pantanal. 1997.

190. Gupta HV, Perrin C, Bloschl G, Montanari A, Kumar R, Clark M, Andréassian V. Large-sample hydrology: a need to balance depth with breadth. Hydrol. Earth Syst. Sci., 18, 463-477, 2014. doi:10.5194/hess-18-463-2014.

191. Borma LS, Tomasella J, Roballo ST, Cuartas LA, Rodriguez DA, Marengo J A, Nobre CA. "Impactos Dos Eventos Extremos de Seca e Cheia Sobre os Recursos Hídricos Amazônicos, Desastres Naturais e Ações da Defesa Civil," In: Borma L S and Nobre C A, Eds., Secas na Amazônia, Oficina de Textos, São Paulo, 2013 (in Portuguese).

192. Marengo JA, Borma LS, Rodriguez DA, Pinho P, Soares WR, Alves LM. Recent Extremes of Drought and Flooding in Amazonia: Vulnerabilities and Human Adaptation. American Journal of Climate Change. 2013, 2: 87-96. Doi: 10.4236/ajcc.2013.22009.

193. Ponce VM. Management of droughts and floods in the semiarid Brazilian Northeast—The case for conservation. J. Soil Water Conservat. 1995. 422-431

194. Gutierrez APA, Engle NL, De Nys E, Molejón C, Martins ES. Drought preparedness in Brazil. Weather and Climate Extremes. 2014; 3, 95-106. doi: 10.1016/j.wace.2013.12.001

195. ANA/DAEE, Agência Nacional de Águas/Departamento de Águas e Energia Elétrica. Resolução Conjunta ANA/DAEE n◦ 1672, 17 de Novembro de 2014 (Brazilian National Water Agency

(ANA)/São Paulo Water and Electrical Energy Department (DAEE) Joint Resolution), Brazil. 2014. Available: http://www.daee.sp.gov.br/images/documentos/ cantareira/ 1672ANADAEE.pdf. Accessed on: [2014-19-11].

196. ANA/DAEE, Agência Nacional de Águas/Departamento de Águas e Energia Elétrica. 2015. Boletim diário ANA/DAEE de monitoramento do Sistema Cantareira situação do sistema equivalente - 06/02/2015, Sistema Cantareira. Available at: http://arquivos.ana.gov.br/ saladesituacao/BoletinsDiarios/DivulgacaoSiteSabesp_6-2-2015.pdf. Accessed on: [2015-02-06].
197. Watts J. Brazil's worst drought in history prompts protests and blackouts. The Guardian, 2015-01-23. Available at: http://www.theguardian.com/world/2015/jan/23/brazil-worst-drought-history. Accessed on: [2015-03-26].
198. Secretária Nacional de Defesa Civil. Ministério da Integração Nacional. Atlas Brasileiro de Desastres Naturais. 2011. Available at: http://150.162.127.14:8080/atlas/atlas.html. Accessed on: [2012-11-26].
199. Seneviratne SI, Nicholls N, Easterling D, Goodess CM, Kanae S, Kossin J, Luo Y, Marengo J, McInnes K, Rahimi M, Reichstein M, Sorteberg A,Vera C, Zhang X, "Changes in Climate Extremes and Their Impacts on the Natural Physical Environment," In: Field C B, Barros V, Stocker T F, Qin D, Dok-ken D J, Ebi K L, et al., Eds. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, New York, 2012, pp. 109-230.
200. Jeong J, Kannan N, Arnold J, Glick R, Gosselink L, Srinivasan R. Development and Integration of Sub-hourly Rainfall–Runoff Modeling Capability Within a Watershed Model. Water Resour Manage. 2010, 24 (15); 4505-4527. Doi: 10.1007/s11269-010-9670-4.
201. Tundisi JG, Matsumura-Tundisi T. Integration of research and management in optimizing multiple uses of reservoirs: the experience in South America and Brazilian case studies. Hydrobiologia. 2003; 500, 231–42.
202. Soares-Filho B, Rajão R, Macedo M, Carneiro A, Costa W, Coe M, Rodrigues H, Alencar A. Land Use: Cracking Brazil's Forest Code. Science. 2014, 344 (6182); 363-364. doi: 10.1126/science.1246663.
203. Rosillo-Calle F. A brief account of Brazil's biomass energy potential. Biomassa & Energia. 2004, 1(3): 225–36.
204. Andrietta MGS, Andrietta S R, Steckelberg C, Stupiello ENA. Bioethanol: Brazil, 30 years of Proálcool. Int. Sugar J. 2007, 109: 195–200.
205. Honrado JP, et al., Can we infer about ecosystem services from EIA and SEA practice? A framework for analysis and examples from Portugal. Environ Impact Asses Rev. 2013, http://dx.doi.org/10.1016/j.eiar.2012.12.002.
206. Daily GC, Polasky S, Goldstein J, Kareiva PM, Mooney HA, Pejchar L, et al. Ecosystem services in decision making: time to deliver. Front Ecol Environ. 2009; 7(1): 21–8. http://dx.doi.org/10.1890/080025.
207. Jeong J, Kannan N, Arnold JG, Glick R, Gosselink L, Srinivasan R, Harmel RD. Development of sub-daily erosion and sediment transport algorithms for SWAT. Transactions of the ASABE. 2011; 54(5): 1685-1691. ISSN 2151-0032.

Appendix A. Internet locations for the majority of data sources listed in Tables 3.4 to 3.7

Institution/Agency	Internet location of data source
Climate/hydrological data sources	
NCEP-CFSR (National Centers for Environmental Prediction - Climate Forecast System Reanalysis)	http://globalweather.tamu.edu/
INMET (National Institute of Meteorology)	http://www.inmet.gov.br/projetos/rede/pesquisa/
EMBRAPA (Brazilian Agricultural Research Corporation)[a]	https://www.embrapa.br/en/home
SIMEPAR (Paraná State Meteorological System)[a]	http://www.simepar.br/site/internas/conteudo/produtos_servicos/pesquisa.shtml
UNESP (State University of São Paulo)	http://www.ipmet.unesp.br/
UFMT (Federal University of Mato Grosso)	http://200.129.241.80/desa/estacaomestrebombled.html
Battistella Florestas Company[a]	http://www.battistella.com.br/
Coruripe Plant[a]	http://www.usinacoruripe.com.br/
Epagri/Ciram (Santa Catarina Agricultural Research and Extension[a] Corporation)	http://ciram.epagri.sc.gov.br/
USP (University of São Paulo)[a]	http://www.estacao.iag.usp.br/ http://www.leb.esalq.usp.br/postoaut.html
ANA (National Water Agency)	http://hidroweb.ana.gov.br/
ANEEL (Brazilian Electricity Regulatory	http://www.aneel.gov.br/
DAEE (Department of Water and Electrical Energy)	http://www.hidrologia.daee.sp.gov.br/
SABESP (Basic Sanitation Company of the São Paulo State)[a]	http://site.sabesp.com.br/site/Default.aspx

[a]The actual data sources may not be directly available on the web; however, the weblinks provided here provide a starting place to contact the responsible agency or person.

Appendix A. Continued

Institution/Agency	Internet location of data source
DEM data sources	
SRTM (Shuttle Radar Topography Mission)	http://www2.jpl.nasa.gov/srtm/dataprod.htm http://www.relevobr.cnpm.embrapa.br/download/[a]
ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer)	http://asterweb.jpl.nasa.gov/data.asp
IBGE (Brazilian Institute of Geography and Statistics - Topographic maps)	http://www.ibge.gov.br/home/geociencias/download/arquivos/index14.shtm
Land use data sources	
USGS (United States Geological Survey - Land Cover Dataassemble several links to data sources)	http://landcover.usgs.gov/landcoverdata.php
FAO (Food and Agriculture Organization) Global Land Cover-SHARE (GLC-SHARE)	http://www.glcn.org/databases/lc_glcshare_en.jsp
INPE (National Institute for Space Research)[b]	http://mtc-m19.sid.inpe.br/col/sid.inpe.br/mtc-m19/2013/07.01.12.41/doc/publicacao.pdf [168] http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0102-77862013000200003[169]
Bahia State Company of Urban Development[b]	http://www.informs.conder.ba.gov.br/produtos.asp
IAC (Agronomic Institute of Campinas)[b]	http://www.iac.sp.gov.br/jndmirim/
FATMA (Environmental Foundation)	http://ciram.epagri.sc.gov.br/index.php?option=com_content&view=article&id=1172&Itemid=543
LANDSAT satellite images	http://landsat.usgs.gov/
SPOT satellite images	http://www.geo-airbusds.com/en/143-spot-satellite-imagery
IKONOS satellite images associated with field surveys	http://www.satimagingcorp.com/gallery/ikonos

[a]SRTM version that has been corrected by EMPRAPA for Brazil.

[b]The actual data sources may not be directly available on the web; however, the weblinks provided here provide a starting place to contact the responsible agency or person.

Appendix A. Continued

Institution/Agency	Internet location of data source
Soil map and property data sources	
FAO-UNESCO (Food & Agriculture Organization- United Nations Educational, Scientific and Cultural Organization)	http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/
Project RADAMBRASIL (Brazilian Government)	http://mapas.ibge.gov.br/tematicos/solos
EMBRAPA (Brazilian Agricultural Research Corporation)	http://www.sisolos.cnptia.embrapa.br/
ISRIC (World Soil Information)	http://www.isric.org/data/data-download
IAC (Agronomic Institute of Campinas)[b]	http://www.iac.sp.gov.br/solossp/
Emater-RS[b]	http://www.emater.tche.br/site/
SEMA - Environmental State Foundation[b]	http://www.sema.mt.gov.br/
Watershed Committee: Alto Paraguay Basin Conservation Plan[b]	http://www.mma.gov.br/port/se/pnma/ecos24.html
Integrated management project for the São Francisco Watershed supported by ANA[b]	http://cbhsaofrancisco.org.br/o-cbhsf/
Water Resources Master Plan for Bahia State[b]	http://www.ana.gov.br/AcoesAdministrativas/CDOC/docs/planos_diretores/Bahia/plano_d

[b]The actual data sources may not be directly available on the web; however, the weblinks provided here provide a starting place to contact the responsible agency or person.

4. *Systematic Procedure for Calibrating Complex Watersheds: Case Study Application in Southeast Brazil*

A modified version of this chapter is in the review process of a peer-review international journal, with the following co-authors: Danielle de Almeida Bressiani, Raghavan Srinivasan, Sabine Sauvage, José Miguel Sanchez Perez, Eduardo Mario Mendiondo

Abstract

Hydrological models involve a large number of parameters to represent the spatial heterogeneity of the watershed and its physical processes. Due to this complexity, the sensitivity analysis, calibration, validation, and uncertainty analysis procedures can become hard and demanding tasks. Several authors have discussed the need to better document and explain the calibration procedures and choices made in watershed modeling. There is no set calibration procedure, and it is highly dependent on, among other factors, model, watershed, goals of the study, available data, modeler's experience and knowledge. This study proposes a systematic methodology, with a step-by-step approach, in which the purposes are to take into consideration different watersheds' dynamics in the calibration process and to assist modelers in developing their validated models for their watershed management goals. This systematic calibration approach has ten main steps: (1) collection and assessment of data and understanding of watershed; (2) definition of where to calibrate/validate and periods; (3) definitions of calibration method, objective function and evaluation metrics; (4) main water balance components volumes and processes representations; (5) definition of parameters and ranges; (6) sensitivity analysis; (7) calibration; (8) validation; (9) cross validation; and (10) uncertainty analysis. This systematic calibration approach was demonstrated and discussed for a case study of a complex watershed in southeast Brazil (the Piracicaba watershed, 12,600 km^2). The case study was successful in demonstrating the broad methodology, as well as in discussing the specifics of the chosen methodologies and calibration steps. Input and output uncertainty analysis was done, showing the non-uniqueness of calibration results.

Keywords: Sensitivity Analysis; Calibration; Validation; Uncertainty Analysis; Watershed Modeling; SWAT model.

4-1. Introduction

Hydrological watershed models are simplifications of reality, with limitations and uncertainties; they are only as realistic as model assumptions, algorithms, data quality and resolution, and parameter estimates. Watershed models enable the investigation of important questions on water resources management. The main goal of watershed modeling is to provide scientific results that can be incorporated into the decision support process so as to allow society, policy makers, and other decision makers to better understand and consider the watershed's processes when planning and taking actions. Since according to its physical characteristics every watershed has singularities and particular behaviors before using the models, for their intended purposes, a careful calibration procedure must be undertaken. The calibration procedure consists on adjusting model parameters based on observed available information to increase the watershed simulation efficiency and capture the watershed's processes and dynamics[1,2,3,4].

Conducting a proper calibration procedure, especially for semi-distributed and distributed watershed models with a large number of parameters that may vary in time and space, is a difficult task that can be very demanding and time-consuming. The calibration and validation procedures can be performed with automatic and manual approaches, or with a combination of both. Nonetheless, the procedures are dependent upon the model used, watershed, and modeler's experience, preferences and knowledge of watershed behavior. The main effort during calibration should be to capture the watershed's dynamics and processes. Calibration performance metrics can appear to have good statistics while misrepresenting the overall processes of the watershed, leading to further errors and misconceptions[1,3,5,6]. This may be due to non-parsimonious modeling in distributed and semi-distributed models; a model with unnecessary calibrated parameters (and/or with overfitting), may become specific for the dataset to which it was fitted, usually a tradeoff between parsimony and goodness-of-fit is needed[7,8,9]. Examples that show how calibrations with proper statistical results and methods may not reflect the watershed physical behavior or provide meaningful results are presented in Arnold et al.[1] and Yen et al.[10]. There is non-uniqueness in the calibration procedures and parameter sets, the concept of equifinality[11] explores this non-uniqueness, in which multiple models and parameter sets may provide acceptable fits to the observed data and should be considered in the uncertainty assessment of the model predictions.

Multiple ecohydrological models have been developed[12,13,14]. Among these, the Soil & Water Assessment Tool (SWAT) is a watershed model widely used and applied for hydrological and environmental assessments[15,16,17,18,19]. Douglas-Mankin et al.[20] assessed calibration results from SWAT-related papers from the Soil & Water Division of the ASABE 2010 collection along with the ones reported by Gassman et al.[18] and found that 69% of 107 calibration results and 56% of 86 validation results rated as satisfactory or better according to model performance criteria from Moriasi et al.[21]. Nevertheless, the authors reported that gaps in calibration methods and presented results were evident in many cases. They concluded that improved reporting of calibration and validation procedures and results, using standard guidelines, is essential to adequately comprehending and comparing studies. White and Chaubey[22] state few published SWAT model applications provide detailed information on sensitivity analysis, calibration and validation of the model. Arnold et al.[23] also state that a comprehensive overview of key aspects of an ideal calibration and validation process is lacking in the literature.

As discussed, the calibration and validation process can be a hard task, and there is little guidance in the literature (especially for new modelers). The aim of this study is to discuss different elements that should be taken into account while performing the calibration/validation/uncertainty analysis procedures. This study should assist with a step-by-step approach to developing validated models for watershed management goals. Specifically, the objectives of this study are to: (a) propose a methodological step-by-step framework for a systematic model calibration; and (b) demonstrate this procedure for a complex watershed in southeast Brazil.

4-2. Systematic Calibration Procedure

Watershed models may simulate different processes, as for example, simulates water, sediment, nutrient and pesticide transport at a watershed scale, in which the water balance is the driving force behind other processes, such as the movement of sediments, nutrients, pesticides, etc[24,25]. Therefore, usually in the calibration sequence hydrology is calibrated first (since it determines the other processes), followed by sediment and then water quality components such as nutrient and pesticide transport. Of course the sequence and what will be calibrated are dependent on the objective of the project. For example if only one set of parameters and model must be used for all these factors, they can be calibrated in the previous sequence, or they may be jointly calibrated in a formulated multi-objective automatic optimization approach[26,27,28].

For this study we discuss the calibration and validation of the hydrology parameters, specifically we discuss flow. There is no set calibration and validation procedure, but in this section we propose a systematic calibration procedure. This procedure is subdivided into main steps that are presented in Figure 4-1, and each step is discussed in more detail in sub-sections 4-2.1 to 4-2.10, we present an example of this procedure applied to the Piracicaba watershed, a complex watershed in southeast Brazil.

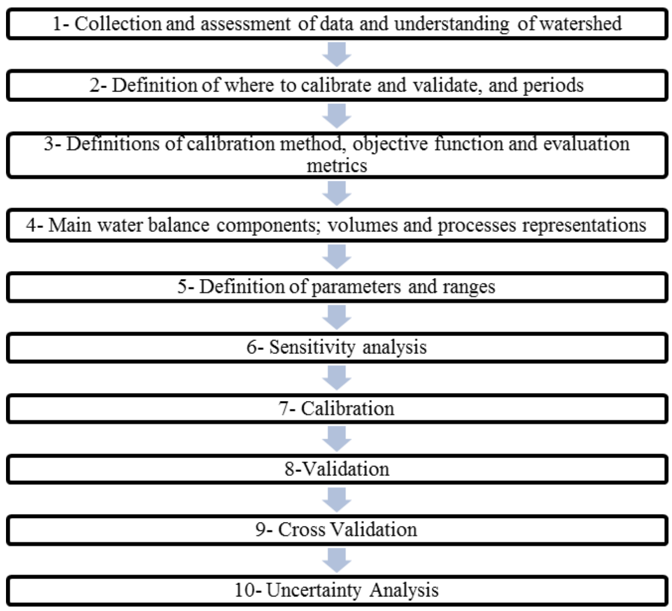

Figure 4-1- Step-by-step of the systematic calibration procedure.

4-2.1. Collection and Assessment of Data and Understanding of Watershed

Lack of sufficient monitoring data, inadequate data needed to characterize input parameters, and insufficient scientific understanding were problems listed by Gassman et al.[18] related to the good representation of processes). Also using remote sensing products can be very helpful.in watershed modeling. Depending on the watershed and region, there may be severe limitations on the data for calibration. It is rare to have a long term time series of all the major hydrology components. But since one of the most important aspects of calibrating and parametrizing is the user's understanding of the watershed and its processes, an assessment of available data is necessary[1,23].

The goals of the study and watershed particularities define which data should be gathered, but as discussed by Arnold et al.[1], Gupta et al.[3], and Siebert and McDonnell[6] there is a need to incorporate "soft data" in the calibration process and not only "hard data". Hard data is measured data, such as time series of flow from stream gauges, groundwater levels from wells, and monitored soil moisture. These data are usually used for calibration. On the other hand, "soft data" is qualitative knowledge from experimentalists or from the scientific literature, as well as from reports, thesis and dissertations, about the studied watershed or a region with similar conditions. Soft data are usually discontinuous and numerically approximated as estimated averages or ranges. Examples include evapotranspiration averages, base flow ratio estimates, average depths of groundwater tables, average vegetation LAI and crop yields[1,6]. The assessment of soft data improves the user's knowledge of the watershed dynamics, providing a consistency test of the processes involved in watershed modeling. This provides parameter ranges and constraints for the calibration process[1,6]. Also using remote sensing products can be very helpful. Soft data is proposed here to be included in the first stage of the calibration procedure, to make sure the process and average annual volumes are being captured in the model (section 4-2.3).

4-2.2. Definition of where to Calibrate and Validate, and Periods.

Based on all available data for the watershed (Step 1), the defined goal of the project, and the watershed's spatial physical characteristics, the watershed area should be subdivided into areas (sub-regions) in which the physical characteristics including soil types, geology, land use, eco-region and topography are similar. If there is only one gauge station with available data, or the watershed has the same characteristics overall, there is not much of a choice, and only one gauge station may be used. If there is heterogeneity within the watershed and available data, the watershed should be calibrated at multiple gauges, based on the defined sub-regions to improve the accuracy of the model predictions and capture the watershed processes. Calibration results taken only at the outlet or at a single gauge station in a heterogeneous watershed may not significantly incorporate the watershed spatial dynamics into the model, and this may cause errors in simulating scenarios. Several authors have discussed and advised multi-site calibration[1,10,22,23,29,30,31].

The calibration and validation periods depend on data availability. When data is available it is common to use a minimum period of 10 years for each (calibration and validation), for monthly and daily calibration. In hourly modeling or with models that demand long processing periods, this can be very much reduced. A common practice when data is more scarce is to use 2/3 of the data available for calibration and 1/3 for validation. The selected periods should incorporate similar ranges of conditions to the ones that the model is expected to reflect. For example if the model is expected to reflect well all hydrological conditions it is important to have dry and wet years[23].

4-2.3. Definitions of Calibration Method, Objective Function and Evaluation Metrics

There is no absolute calibration method; many diverse methods have been used and discussed in the literature[32,33,34,35,36,37]. The method used depends on watershed complexity, model used, number of parameters addressed, project goals, and user experience and preference. Methods range from iterative manual only to combined manual iterations with automated methods to fully automated methods[4,23].

Manual calibration, especially for complex hydrologic models with a large number of parameters, can become labor-intensive and difficult. Success is highly dependent upon modeler experience. Auto-calibration uses optimization methods to determine best fit, and it may be less subjective and require less labor[4,21,23,38]. Also, many approaches combine the two techniques. Manual calibration can initially be used to better understand the model and important processes. For example, one can start by calibrating volumes and/or potential evapotranspiration and then fix a range of initial values for the parameters, or start with a manual calibration for parameters that are easily interpreted, as curve number. Then one can proceed to the automatic calibration step. The opposite can also be done: auto-calibration can be used to select and reduce parameter ranges with less labor to start the calibration, and final adjustments can be made with manual calibration, as to maintain mass balance and adequately represent the range in magnitude of output variables[39]. Using both techniques combines their strengths and can facilitate the calibration process[39,40].

For an automatic optimization option the user may need to build own auto-calibration method, depending on the objective and model used. There are open source tools, as the Model-Independent Parameter Estimation and Uncertainty Analysis program (PEST)[41], which is widely used in calibration of hydrological models[27,42,43,44,45]. For specific models automatic calibration tools may exist, as for the Soil and Water Assessment Tool (SWAT)[15,25] there is the SWAT Calibration Uncertainty Procedures (SWAT-CUP) software[46], as also a developed framework in R-software; R-SWAT-FME framework[47,48] and an SCE module that was directly incorporated into the SWAT code[49,50].

The calibration method used for the case study presented in section 4 was SWAT-CUP[46], and the algorithm used was the Sequential Uncertainty FItting (SUFI-2). One advantage of using SUFI-2 is that it provides a semi-automated approach where the user can perform both manual and automated calibration, adjusting and updating the parameters and its ranges between auto-calibration simulations[32,23]. Yang et al.[37] tested different methods for calibrating SWAT and found that SUFI-2 required much fewer simulations to obtain similar performance criteria results. There are many publications applying SWAT using SWAT-CUP and SUFI-2 for calibration, validation and/or uncertainty analysis [32,37,51,52,53,54,55].

There are many different possible ways for formulating an objective function and each may lead to a different calibration result. The choice of the calibration permanence measure (objective function) may depend on the phenomena in interest and the goal of the model. For example the Nash-Sutcliffe (NSE)[56], a much known measure in hydrology, is known to be biased for high flows, while an alternative logarithmic form may be interesting to emphasize low flows. Krause et al.[57] and Price et al.[58] discuss how measures can adjust differently to capture high or low streamflows. Shafii and Smedt[27] used a multi-objective approach with a compromise using two permanence measures for equal attention to low and high flows, comparing with single objective optimization approaches for a distributed hydrological model (WetSpa)[59]. Many studies have discussed the use of multi-objective functions[26,27,28,49,60,61,62]. Also, many studies have discussed the importance of assessing the calibration process and results with different evaluation metrics, with a multiple statistical criteria to make sure the calibrated model results are reasonable for different conceptual statistics[57,63,64,65].

As discussed, in the calibration process it is very important to ensure that the processes inside the watershed are being captured so that land use, management, and/or climate scenarios can provide meaningful information. To accomplish this, we propose first a manual calibration step to evaluate the major components of the water balance and the behavior of the main processes, analyzing the simulation with soft data and/or averages of hard data (obtained in the first step- 4-2.3). We also suggest doing verification or a “pseudo” calibration using remote sensing products with the model’s outputs prior to closely calibrating streamflow/high flow/baseflow. This can be very desirable to make sure some processes are reasonable and within the expected ranges. This evaluation of the major components of the water balance is an important step in the calibration; it’s purpose is to identify if there are important problems or misrepresentations that may lead to the need to change methods or adjust input data to different sources and/or better resolution.

The goal is to represent well overall the water balance components in the model, such as average flows, base flow ratios, evapotranspiration (ET), potential evapotranspiration (PET), and vegetation growth. These aspects affect the other components of watershed modeling. For example, ET has a large impact on the water balance, usually being the largest component of it. ET is modeled as function of PET and, at the same time, vegetation growth affects ET and hydrology in general (canopy volumes). Vegetation growth also affects and is affected by nitrogen and phosphorus concentrations and carbon matter generation. Runoff affects the generation of sediment, and flow leads to the dilution of water quality components and sediment transport[1,23,66,67,68].

4-2.5. Definition of Parameters and Ranges

The selection of parameters and their ranges is subjective and dependent upon the modeler’s experience with the hydrological model and their knowledge of watershed behavior. Many watershed models are process-based and therefore the choice of parameters should relate to the processes that need improvement in the calibration procedure, and parameters must be attributed with physically meaningful ranges for the region. These distributed and semi-distributed models have several different parameters, we advise the user to consult the models documentation for more details. For example for the SWAT model, we advise the user to consult the SWAT Input/Output Documentation and the Theoretical Documentation[24,25] to better understand the parameters and processes. As well as one can refer to selected parameters for calibration based on the literature, for the SWAT model tables of these selected parameters can be found on Muleta et al.[4], White and Chaubey[22], Douglas-Mankin et al.[20], Srinivasan et al.[69] and Arnold et al.[23]. For this initial step, it is advised to use expert knowledge and knowledge obtained from the previous section 4-2.3 on the dominant processes and characteristics of the region.

4-2.6. Sensitivity Analysis

Model outputs are not equally sensitive to different model parameters and may vary for different regions and watersheds. Identifying which parameters are more sensitive is very important to decrease the efforts in the calibration step. Sensitivity analysis is the process of determining variability in model output with respect to changes in input parameters. There are several techniques for conducting sensitivity analysis; they are usually classified as local or global approaches. Local approaches analyze the variability of model output to changes of one model parameter while the others remain constant; therefore they do not account for interactions between parameters. Global sensitivity analysis approaches measure output variability accounting for changes in all of the selected parameters at the same time [4,23,70,71,72].

The sensitivity analysis (4-2.6), calibration (4-2.7) and validation (4-2.8) steps were conducted first for monthly (4.3.6, 4.3.7) and then for daily (4.3.8, 4.3.9, 4.3.10) time steps. It is important to first calibrate for monthly time step, making sure to incorporate the major processes and volumes, and then for fine-tuning and timing adjustments continue to daily and then sub-daily time steps (if there is available data and interest to model at this time step).

4-2.7. Calibration

This step will depend on the calibration method, objective function and evaluation metrics chosen in Step 4-2.4, but for all types of calibration we advise the user to pursue the diagnostic approach of studying the behaviors of the observed and simulated hygrographs, identifying where there is room for improvement and which parameters represent the different processes that should be addressed[23,73]. It is important to first calibrate for monthly time step, making sure to incorporate the major processes and to adjust volumes, and then to go to daily calibration, to refine and mainly adjust timing. With the information from the first recognition sensitivity analysis and the defined parameter intervals (with physical meaning for the area), the calibration parameters can be determined by the user. The calibration process consists in changing parameter values and evaluating the differences between model outputs. Calculating different evaluation metrics to analyze possible distinct components on the calibration performance is advised[57]. Until reaching satisfactory or good results, the criteria of which being dependent upon many factors such as the goal of the project, the datasets used, etc. Based on the literature[21] proposed performance ratings for model evaluation, Table 4-1.

Table 4-1. Model Performance Ratings for monthly time-step[21]

			PBIAS (%)		
Performance Rating	RSR	NSE	Streamflow	Sediment	N, P
Very Good	$0.00 \le RSR \le 0.50$	$0.75 < NSE \le 1.00$	$PBIAS < \pm 10$	$PBIAS < \pm 15$	$PBIAS < \pm 25$
Good	$0.50 < RSR \le 0.60$	$0.65 < NSE \le 0.75$	$\pm 10 \le PBIAS < \pm 15$	$\pm 15 \le PBIAS < \pm 30$	$\pm 25 \le PBIAS < \pm 40$
Satisfactory	$0.60 < RSR \le 0.70$	$0.50 < NSE \le 0.65$	$\pm 15 \le PBIAS < \pm 25$	$\pm 30 \le PBIAS < \pm 55$	$\pm 40 \le PBIAS < \pm 70$
Unsatisfactory	$RSR > 0.70$	$NSE \le 0.50$	$PBIAS \ge \pm 25$	$PBIAS \ge \pm 55$	$PBIAS \ge \pm 70$

4-2.8. Validation

Validation is a robustness verification of the calibrated model using statistics and graphs, in which the same set of calibrated parameters are kept and the simulated results are compared to data of a different time period. It is an important step because it provides an evaluation of the parameter changes made in the calibration process and tests whether the model with these parameters can have similar performances in different climate conditions. Validation is an essential test for over-fitting; a common issue in complex watershed modelling, when limited and noisy data sets are used to infer the model parameters leading to overparametrization. It may show deficiencies in the calibrated model. Deficiencies may especially arise if the calibration period is small and the parameters changed are adjusted for a particular condition range which may not be significant for a different range of climate situations that may arise in the validation period. The criteria evaluation can be the same used for calibration (4-2.7).

4-2.9. Cross-Validation

Cross-validation can be considered a common practice of the split testing in hydrology (which divides the dataset in two: one for calibration and another for validation). In the k-fold cross-validation the entire dataset is split into k subsets, and the performance metrics are quantified for the k validation subsets, based on the calibrated model[74,75]. A cross-validation is simple, robust and makes use of all the data providing better verification. It should be performed to evaluate if interior process simulation and calibrated parameters are accurate, not only for the gauge stations where calibration and validation were performed, but also for other gauge stations in the watershed. This cross-validation should be performed whenever quality data exists for multiple gauge stations within the watershed.

4-2.10. Uncertainty Analysis

It is impossible to understand, represent and reproduce the totality of factors that influence and describe all processes related to watershed and hydrological modeling. There are a number of simplifications and approximations in the models themselves (where processes are mathematically simplified representations). There is a lack of complete information and data, as well as uncertainties within the measured data and parameter estimates (values and ranges, as temporal and spatial variability). The uncertainty is unavoidable and should be analyzed and considered during the entire process of watershed/hydrological modeling and further assessed. It has an even greater importance because these models are often used for decision making. The watershed modelling uncertainties can be classified into three basic categories: model uncertainty, parameter uncertainty, and uncertainty inherent to the natural processes[76]. In this application we address model input, or parameter uncertainty and model uncertainty, looking into model output uncertainties. This topic has been greatly researched and discussed[9,11,33,76,77,78,79,80,81].

4-3. Case Study Application in Southeast Brazil

4-3.1. The Watershed Model – Soil and Water Assessment Tool (SWAT)

The systematic procedure for calibration will be demonstrated with the Soil and Water Assessment Tool (SWAT)[15,16]. It is a product of about 40 years of *United States Department of Agriculture - Agricultural Research Service* (USDA-ARS) modeling experience[18,19,23]. It is a hydro-agro-environmental physical-based complex semi-distributed model. SWAT is usually operated on a continuous daily time-step and simulates water, sediment, nutrient and pesticide transport, crop growth, and management practices at a watershed scale[23,20,18,83]. SWAT is internationally accepted as a robust interdisciplinary versatile watershed model, having being applied in many studies around the world[18], and in well over 100 published studies in Brazilian watersheds[17].

SWAT's driving force is the water balance, taking into account the upland and channel processes[23]. SWAT simulations are constructed by delineating a watershed into multiple subbasins that are further divided into lumped hydrologic response units (HRUs). HRUs consist of a homogeneous combination of land use, soil, and slope characteristics and are not spatially identified within the given subbasin[20,18]. The surface runoff volume is estimated using the Green-Ampt method[84] or a modified version of the Soil Conservation Service (SCS) curve number (CN) method[85], in which the daily CN value can be calculated as a function of soil moisture or as a function of plant evapotranspiration. The potential evapotranspiration can be calculated by the Penman-Monteith[86,87], Priestley Taylor[88], or Hargreaves methods[89], or it can be inserted by the user. For channel routing, the variable-rate storage method[82] or the Muskingum method[90,91] can be used. Groundwater return flow is simulated through a shallow (unconfined) aquifer[92,93], and lateral flow is simulated by a kinematic storage model[94].

To set up a model for SWAT, geographic information systems are usually used. These include the ArcSWAT interface in ArcGIS, MWSWAT in MapWindow, and QSWAT in QGIS (all versions available on http://swat.tamu.edu/software/). The model requires topographic, soil, and land use maps, as well as climate data, crop management data, inflow and point sources data, and streamflow and available data for calibration and validation.

4-3.2. The Demonstration Watershed

The Piracicaba watershed (Figure 4-2) in southeast Brazil was chosen for this study to demonstrate a systematic methodology for calibrating the hydrology of a complex watershed. The 12,600 km² Piracicaba watershed is part of the Paraná watershed, with average yearly precipitation of 1400 mm and average monthly flow of 135 m^3/s (at downstream Gauge Station 16, Figure 4-2). It is a very relevant watershed for supplying water to the São Paulo Metropolitan Region, but also for its diverse land uses. The Piracicaba watershed is predominately rural and mainly covered with sugar cane and pasture, but it has considerable areas with forest cover, eucalyptus and citrus plantations, and urban areas (in which about 3.5 million people live).

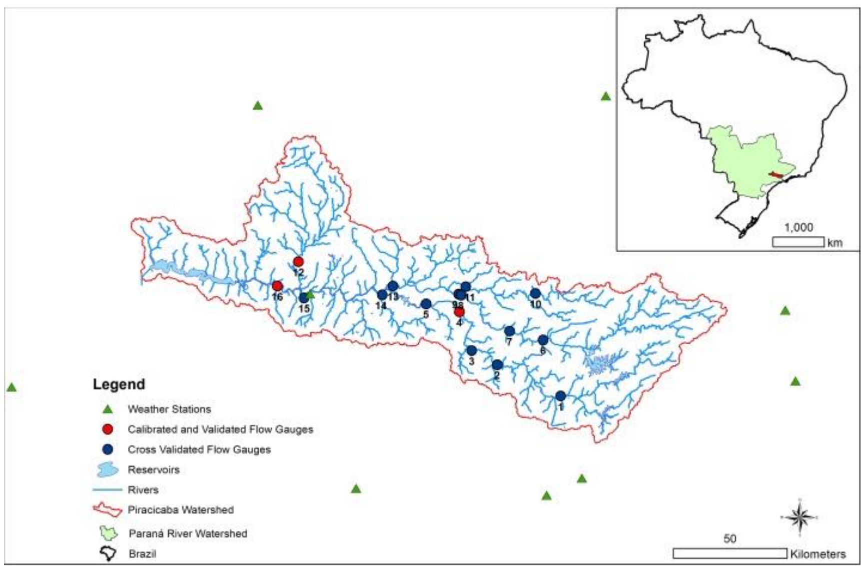

Figure 4-2 - - Location of Piracicaba watershed, and weather and streamflow gauge stations.

It is also a very relevant watershed because it has high hydrological variability. It has episodes of high flows with flooding problems, such as on January 7th 2011, when flow reached 1000 m^3/s, flooding large areas[95]. The watershed is also prone to severe droughts, such as the recent exceptional drought of 2014/2015, with the lowest observed flow records since the watershed started to be monitored. On November 22nd 2014 the flow reached 3.46 m^3/s, 96% smaller than the historic average for the month. In this period the reservoirs' volumes of the Cantareira System decreased to around 5% of their full capacity in January 2015, with the dead volume being pumped for the water supply of the São Paulo metropolitan region [96,97,98,99,100].

4-3.3. Model Setup and Data Sets

The Piracicaba SWAT model setup was constructed with ArcSWAT interface on ArcGIS 10.0 [101]. It requires topographic, soil, land use and climate data, as well as streamflow and available data for calibration, validation and uncertainty analysis. The model was constructed using information freely available from the web or provided by government and water management agencies. The Digital Elevation Map (DEM) (Figure 4-3)) was built from the United States National Aeronautics and Space Administration (NASA) and Japan's Ministry of Economy, Trade, and Industry (METI) public domain Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM data[102], which consists of 1 arc-second, approximately 30 m resolution. The 1:50,000 land use map used (figure 3b)) was developed from Landsat 5 TM 2010 images with approximately 30 m-pixel resolution [103] and the soils map (1:500,000) used was from Oliveira[104] (Figure 4-3- c).

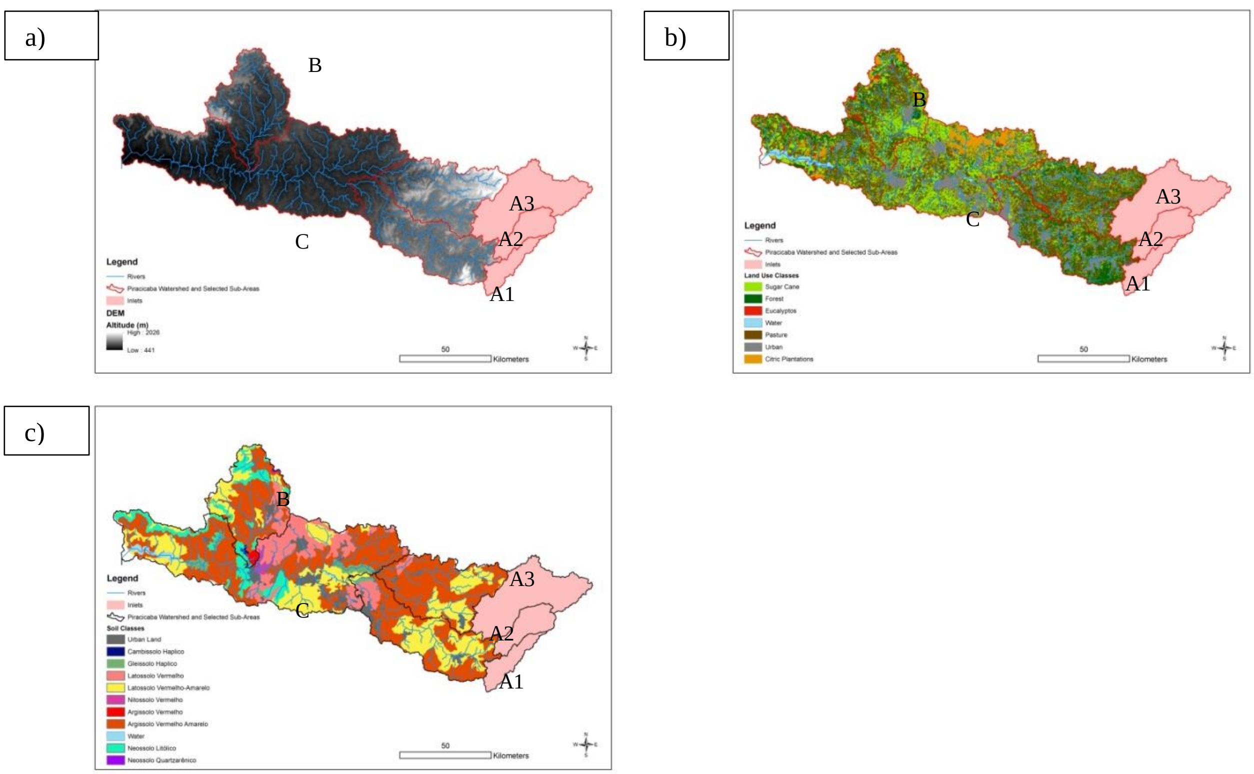

Figure 4-3 – Piracicaba watershed digital elevation model (a), land use map (b), and soils map (c).

The delineation of the streams and watersheds was conducted in ArcSWAT based on the DEM with a minimum drainage area of 10 km^2. The number of subbasins was 523, with an average area of 20 km^2, and 7420 HRUs. The area of the modeled watershed is 10,454 km^2. The areas of the watershed upstream of the Cantareira system reservoirs were not modeled on the SWAT project; instead the contribution of the area was considered as inlets and the reservoirs' discharges were accounted as inputs to the model. Polynomial regressions between the inlet and a more downstream station were stablished on Excel for the three inlets. These regressions were used to complete the flow time series if the missing data was less than ten consecutive days. If more than ten days of reservoirs' discharges data were missing, a long-term monthly average for the period was used.

Soil characteristics (soil depths, texture, and organic matter) were based on the soil profiles from São Paulo State[104]. The hydrological group was adopted following the Brazilian soils classification from Sartori et al.[105], and Pedo-transfer Functions (PTF)[106] were used to estimate the other soil parameters needed for SWAT. Six main categories were defined in the land use map: pasture, sugarcane, forest, eucalyptus, citrus plantations and water. For the forest, eucalyptus and citrus plantations, different crop parameters (initial leaf area index, initial biomass, total number of heat units needed for growth, and the minimum and maximum values of leaf area index) were adjusted to better fit the conditions of the area, since the LAI variations in the different seasons are smaller in the tropical climate conditions than in temperate climates, and the crops were already established in the watershed. For sugarcane, a five year rotation was established with nitrogen and phosphorous fertilizations based on discussions with local farmers. Fertilizer application is an important procedure for plant growth (otherwise it would suffer from nutrient deficiency). Plant growth affects the canopy intersection, evapotranspiration, etc, therefore the water balance of the study area.

Daily historical data related to precipitation and flow from 1975 to 2011 were obtained from ANA[107] and DAEE[108](Figure 4-2). Precipitation data spatio-temporal distribution is highly important for modeling; since SWAT uses one precipitation gauge per subbasin and there is a highly diverse spatio-temporal distribution of rainfall in the watershed, the precipitation records from all gauge stations were interpolated to establish a model with one interpolated precipitation data series per subbasin. The interpolation was done with the PCP_SWAT ArcGIS plug-in program [109], and different interpolation methods were tested. These methods included Thiessen Polygons[110] and Inverse Distance Weighted (IDW)[111]. The Inverse Distance Weighted (IDW) was chosen because it presented better geostatistical results. Daily maximum and minimum temperatures, wind speed, humidity and insolation were obtained from the National Meteorological Institute[112] and from one station at the University of São Paulo[113] (Figure 4-2), while missing data was generated in SWAT based on monthly statistics created from long-term measured available data. Solar radiation values were estimated based on insolation from the weather station network [114,115,116].

4-3.4. Application of the Systematic Calibration Procedure

4-3.4.1. Collection and Assessment of Data (Soft and Hard) and Understanding of the Watershed

As a first step for calibration, a data gathering phase was done, which included hard and soft data for calibration and better watershed understanding. Information from different related agencies were assessed (with some agencies visits and meetings were conducted); these included the National Water Agency (ANA); São Paulo State Water and Electrical Energy Department (DAEE); Hydraulics Technological Center Foundation (FCTH-SAISP); Brazilian Center of Monitoring and Early Warning of Natural Disasters (CEMADEN); São Paulo State Basic Sanitation Company (SABESP); Remote Sensing data from MODIS; Brazilian Corporation of Agricultural Research(EMBRAPA); Brazilian Institute of Geography and Statistics (IBGE); Geological Survey of Brazil (CPRM); and the Watershed Committee (Piracicaba-Capivari-Jundiaí, CBH-PCJ), among others. Each contribution is cited in the following text. Published literature, thesis and dissertations were studied, and specialists in the area such as local farmers, university professors and water agency professionals were consulted.

4-3.4.2. Definition of Where to Calibrate and Validate, and Periods

The Piracicaba watershed was sub-divided into three main regions (A, B and C) based on physical characteristics (Figure 4-3). Region A has a larger forest area and less agricultural uses, as well as higher altitudes and slopes, with a mean average slope of 15%. Region A also has higher drainage density, with deep soils and a geology of crystalline bedrocks, and it’s eco-region vegetation is classified as Atlantic Forest. The central and western areas of the watershed are another eco-region type, known as Cerrado (a type of Savannah). These areas of the watershed are characterized by smaller vegetation, sedimentary bedrock, and larger areas of sugar-cane and agriculture production, as well as lower slopes and altitudes. Region B has more forest area and higher altitudes than the lower lands of the more agricultural Region C. Region C has slightly different climatic conditions from B, including less precipitation [117,118,119,120].

The time series available ranged for the different stations, but there was sufficient data from 1975 to 2011 for the inlets and for the calibration and validation periods. Therefore, it was decided to use the first five years to warm-up the SWAT model and the last eleven (2000-2011, although one of the flow gauge station, Station 12, does not have data in 2000 and 2001) years for calibration, since the land use map used is recent (2010) and the focus of modeling this watershed is for situations close to the present reality. The validation period was established from 1980 to 1999 (20 years).

4-3.4.3. Definitions of Calibration Method, Objective Function and Evaluation Metrics

A semi-automated approach was used for the calibration of the Piracicaba watershed with SWAT-CUP software. The SUFI-2 algorithm and manual input were used. SUFI-2 represents input parameter uncertainty as uniform distributions, while the output uncertainties are considered through the estimation of *P-factor*, which is the percentage between the measured data and the 95% prediction uncertainty band (95 PPU). The 95 PPU is calculated at the 2.5% and 97.5% levels of the cumulative distribution of the outputs of variables obtained from Latin Hypercube Sampling. The *R-factor* is the width of this 95 PPU band divided by the standard deviation of the observed data. The goodness of fit and uncertainty of the calibration are examined at every step by the balance between *P* and *R-factors*[32,55,121].

SUFI-2 (in SWAT-CUP) allows flexibility in the choice of the objective function, with eleven options: a multiplicative form of the square error[32,122]; a summation form of the square error[32,122]; the coefficient of determination (R^2); the Chi-squared (Chi^2); the Nash-Sutcliffe (NSE)[56]; the coefficient of determination multiplied by the line regression coefficient (bR^2); and the fitting between the frequency distributions of observed and simulated series (SSQR)[49]; percent bias (PBias)[2], ratio of the root mean square error (RMSE) to the standard deviation of measured data (RSR)[14], the Kling and Gupta efficiency (KGE)[123] and the modified Nash-Sutcliffe efficiency (MNS)[21,57, 58].

Nash-Sutcliffe (NSE) was chosen as the objective function. The major objective of the model simulation for the watershed is for high flows, and NSE overemphasizes large flows, having squared deviations[63,57,124]. For each iteration and for performance evaluation, a multiple statistical criteria was used, calculating percent bias (PBias), Root Mean Squared Error (RMSE), Normalized Mean Squared Error (NMSE'), coefficient of determination (R2), and the coefficient of determination multiplied by the line regression coefficient (bR2) [21,26,57].

4-3.4.4. Main Water Balance Components; Volumes and Processes Representations

Potential Evapotranspiration Averages

By examining first the main components of the water balance without changing any parameter or default settings of SWAT, the evapotranspiration (ET) and potential evapotranspiration (PET) values seemed low for the region. An important and sensitive parameter that has a direct impact on evapotranspiration is the soil evaporation compensation coefficient (ESCO) [23,125]. The default value of ESCO is 0.95, and decreasing the ESCO value increases the ability of the model to extract evaporative demand from lower soil layers [25]. Since the Piracicaba watershed is on the tropical center climate zone, classified as humid, semi-humid, mild mesothermal and sub-hot [17, 126,127] and because of its latitude, an expected range of ESCO values would be from 0.65-0.90. The ESCO value of 0.70 was manually calibrated. Also, since the PET values were being underestimated, other PET methods (Penman-Monteith, Priestley Taylor and Hargreaves) were tested. Bressiani et al.[128] discussed high SWAT model sensitivity to the different PET methods and weather data for a semi-arid region in Brazil, and they emphasized the need to test and compare the different methods for specific study regions and weather input data.

The default SWAT simulation comparing yearly averages over the entire watershed (Scenario 0) using the Penman-Monteith method and an ESCO value of 0.95 resulted in an ET value of 500 mm and a PET of 985 mm. Changing the ESCO value to 0.7 while maintaining the Penman-Monteith method (Scenario 1) resulted in the ET value increasing to 663 mm (an increase of about ~32%). Using the Priestley Taylor method (with ESCO=0.7) (Scenario 2) the ET yearly average value rose to 936 mm (an increase of about 87% over the SWAT default) and the PET value rose to 1422 mm. The Hargreaves method (with ESCO=0.7) (Scenario 3) yielded an ET value of 1001 mm and a PET of 1589 mm. From the literature and estimated values (soft data), the ET in the watershed ranges from 800-1200 mm and PET ranges from 1040-1500 mm [129,130,131,132,133,134].

In Figure 4-4, the average observed and various simulated monthly regime curve for Gauge Station 4 are presented, with the NSE and PBias. From these analyses we could conclude that Penman-Monteith method is not performing well for the modeled watershed. This may be related to wind speed data, since the Priestley Taylor and Hargreaves methods (which do not use wind speed data) have better results. From checking the wind speed data, we found significantly higher values of wind speed for the weather station in the city of Piracicaba (the only weather station inside the watershed). This may be one reason for the underestimation of ET and PET values using Penman-Monteith. Both Priestley Taylor and Hargreaves methods presented better results, although Hargreaves seems to slightly overestimate the PET values. The yearly flow averages obtained from the four simulations at the three gauge stations revealed that there was an overprediction of flow using Penman-Monteith Method, and that the Priestley Taylor Method was closer overall. Therefore, Priestley Taylor was the chosen method (Figure 4-4).

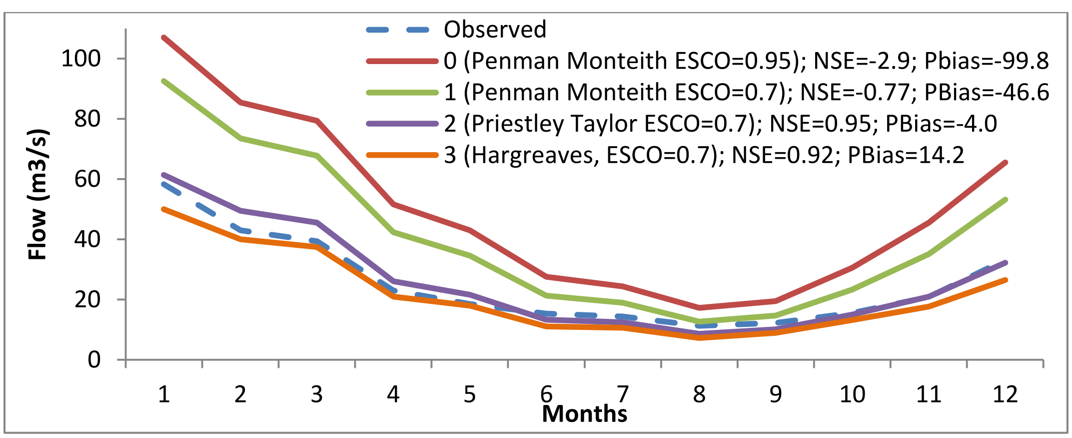

Figure 4-4 - Simulated and observed monthly average flows over the period for Gauge Station 4

Remote Sensing Evapotranspiration Comparison

Evapotranspiration (ET) information and proper estimation is essential for agriculture and water resources management applications[52]. Remote sensing provides spatial and temporal dynamic explicit information on land surface characteristics and has long been recognized for providing the most feasible spatially distributed regional ET information[135]. The implementation of these data in physically-based models can be of great benefit, for comparison of estimates, as well as for calibration, especially on ungauged watersheds[136]. Satellite remote sensing ET data from the MODerate Resolution Imaging Spectroradiometer (MODIS), from NASA's Terra and Aqua satellites was compared over 10 years with SWAT simulated ET.

MODIS ET product is estimated using an algorithm from Mu et al.[135], improved over Mu et al.[137]. The ET algorithm is based on Penman-Monteith equation [86]. This algorithm uses MODIS land cover, albedo, leaf area index (LAI), and Enhanced Vegetation Index (EVI) and daily meteorological data from NASA's Global Modeling and Assimilation Office (GMAO) reanalysis dataset as inputs for regional and global ET mapping and monitoring[135,137].

The MODIS 1km grid cell with 8-day ET resolution was averaged on a monthly time-step for each SWAT delimited sub-basin. A ten year period (2000-2009) was compared with the SWAT monthly ET estimates. Coefficient of determination (R^2) and percent bias (PBias) were calculated. Overall the results seem reasonable with average R^2 value of 0.73. Only 1% of subbasins had R^2 lower than 0.5 and 70% had good agreements, with R^2 values larger than 0.7. In relation to PBias, the average absolute value was 22. In 73% of the subbasins PBias were smaller than 25 (absolute) and in 82% smaller than 40. Subbasins presented large PBias values, in most of these cases there were considerable amounts of water and/or urban land covers. According to Velpuri et al.[138] the MODIS data masks out regions corresponding to water bodies, urban and barren lands.

Also it is very important to note that none of these ET products (MODIS and SWAT) are observed values; they are both modeled results that carry relative uncertainties and were calculated based on totally different processes and databases. Therefore differences were expected. Although both methods have used similar PET equations (Penman-Monteith in

MODIS and Priestley Taylor was used for SWAT), the inputs for these equations were totally different, especially rainfall (which is the major factor in ET, other than soils) that for MODIS NASA's GMAO dataset is used, and in SWAT local interpolated gauge stations data were used.

In Figure 4-5 we present the R^2 values for all the subbasins of the modeled watershed. One can see that the results show good agreements between the estimated evapotranspirations from MODIS and from SWAT, the results that seem worse are in areas between cities and close to citrus plantations, also the area in the central low region of the watershed has warmer climate and the area upstream on Sub-region B is an area with colder weather, these relative changes and climate particularities may have not been as well reproduced by the weather stations used for SWAT. On Table 4-2 we present R^2, PBias and yearly average ETs from MODIS and SWAT for a representative subbasin of the three major land-uses of the watershed (land use area larger than 70% of subbasin area). As expected the area with forest cover had a considerable larger amount of evapotranspiration, and pasture (for the compared subbasin) had the best agreement between SWAT and MODIS ET estimates.

Table 4-2 Evapotranspiration and performance metrics for major land uses

	Sugar-Cane	Pasture	Forest
Land-use percentage area on subbasin	82%	72%	89%
R^2	0.65	0.73	0.88
Pbias	-18.2	-3.3	19.5
MODIS Yearly Average	703.4	849.7	1287.6
SWAT Yearly Average	831.2	878.1	1037.1

Calculated based on monthly evapotranspiration estimates from MODIS and SWAT for a 10 year period (2000-2009)

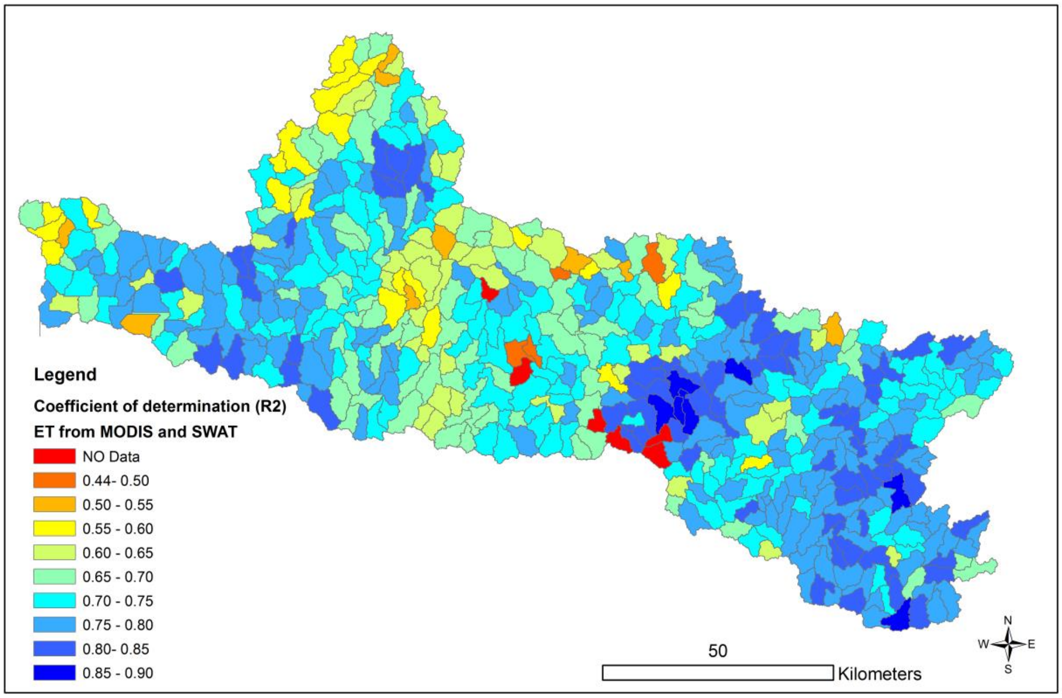

Figure 4-5 - Coefficient of Determination (R2) for evapotranspiration from MODIS and SWAT by Subbasin

Baseflow and Groundwater Parameters

Other important aspects of hydrology are the flow components: base flow and surface runoff contributions. Digital filters can be used to split the flow contributions using daily flow gauge data; in this study the Baseflow Filter program[140,93] available on the SWAT web site (http://swat.tamu.edu/software/) was used to ensure that overland processes were properly simulated. This step is important in order to better represent the components of the water balance, which will affect the other processes. For example, if surface runoff is overestimated then sediment transport and associated pollutants are also overestimated. All available gauge stations were used for separation of base flow, and they were checked against the percent average base flow contribution simulated in SWAT. The Baseflow Filter program also can estimate the base flow recession constant, or ALPHA_BF, that is one of the model parameters. The program was used to estimate the ALPHA_BF values, the average values were 0.06 for A1 and A2, 0.03 for A3 and B, and 0.05 for region C. The region also has deep soils and deep aquifers. The initial depth of water in the shallow aquifer was considered to be 4000 mm (SHALLST), and in the deep aquifer it was considered to be 10,000 mm (DEEPST).

Vegetation Growth

Another important factor of the watershed simulation is the vegetation growth. In the Piracicaba watershed, sugar cane is one of the most important crops and covers a large area. The yield generated in SWAT was verified; the average dry weight biomass simulated in SWAT was 22.5 tons per hectare (tn/ha), which converts to approximately 75 tn/ha of sugar-cane yield[139]. The average productions vary between 94 tn/ha in the state of São Paulo and 70 tn/ha in Brazil[141,142], hence the average values were considered to be reasonable.

4-3.4.5. Definition of Parameters and Ranges

Any distributed or semi-distributed watershed model, has many different parameters, for example for the SWAT model we advise the user to consult the model Input/Output Documentation and the Theoretical Documentation[24,25] to better understand the parameters and processes. Some authors [4,22, 20,23,69] present tables with selected parameters for calibration that are based on the literature.

This methodology first selected a range of 15 to 20 parameters (Table 4-3), each one with a range of values based on the listed parameters on the literature[4,20,22,23,69] as well as knowledge of the watershed and experts' knowledge of the model. In the following steps, the parameters were assessed in relation to their sensitivity and the processes in which they play a major role. This was the first selected parameters, the goal was to reduce the number and ranges of the parameters making it easier calibrate the model.

Table 4-3 Selected parameters, files, meaning and related process

Parameter Name and File	Meaning	Related Process and Calculations
ALPHA_BF.gw	Base flow recession constant	Base flow and shallow aquifer
CANMX.hru	Maximum canopy storage (mm)	Canopy storage
CH_K2.rte	Effective hydraulic conductivity in main channel alluvium (mm/h)	Transmission losses, routing
CH_N1.sub	Manning's "n" value for tributary channels	Peak rate
CH_N2.rte	Manning's "n" value for the main channel	Channel flow, routing
CN2.mgt	SCS curve number (moisture condition II)	Surface runoff
CNCOEF.bsn	Plant ET curve number coefficient	Surface runoff
ESCO.hru	Soil evaporation compensation coefficient	Soil evaporation, Evapotranspiration
GW_DELAY.gw	Groundwater delay time(days)	Shallow aquifer, groundwater
GW_REVAP.gw	Groundwater "revap" coefficient	Shallow aquifer, groundwater
GWQMN.gw	Threshold depth of water in the shallow aquifer for return flow to occur (mm)	Shallow aquifer, groundwater
HRU_SLP.hru	Average slope (m/m)	Peak rate and lateral flow
LAT_TTIME.hru	Lateral flow travel time (days)	Lateral flow
OV_N.hru	Manning's "n" value for overland flow	Peak rate
RCHRG_DP.gw	Aquifer percolation coefficient	Shallow aquifer, groundwater
REVAPMN.gw	Threshold depth of water in the shallow aquifer for revap to occur (mm)	Shallow aquifer, groundwater
SLSUBBSN.hru	Average slope length (m)	Peak rate
SOL_AWC(..).sol	Available water capacity	Percolation
SOL_K(..).sol	Saturated hydraulic conductivity (mm/h)	Lateral flow and percolation
SURLAG.bsn	Surface runoff lag coefficient	Surface runoff lag

4-3.4.6. Monthly Sensitivity Analysis

For an initial sensitivity analysis at a monthly time step, a global sensitivity analysis approach was chosen to account for the interactions between the different parameters. This was performed on the SWAT-CUP software using the SUFI-2 method (section 4-2.3). The sensitivity of the parameters is calculated, applying a multiple regression system from the Latin Hypercube-generated parameters against the objective function values, and then a t-test defines the relative significance of each parameter. The t-stat provides a measure of sensitivity, in which the larger absolute values are the most sensitive and p-values determine the significance of the sensitivity. P-values closer to zero are more significant[46]. Nonetheless this relative significance of the parameters indicated by t-test is subjective to parameter ranges, so sensitivity analysis results may change between different calibration iterations when parameter ranges are changed.

Figure 4-6 presents the sensitivity analysis for the Piracicaba watershed, for monthly and daily time steps, for Sub-region A1, Gauge Station 4. Variability between the daily and monthly sensitivity analysis can be seen. Sensitivity analysis of the daily time step will be discussed in section 4-3.4.8. For the monthly time step, the most sensitive parameter is GW_Delay (groundwater delay time), with the highest absolute t-stat, followed by CN2 (the SCS runoff curve number), and then by the GW_REVAP (the groundwater "revap" coefficient).

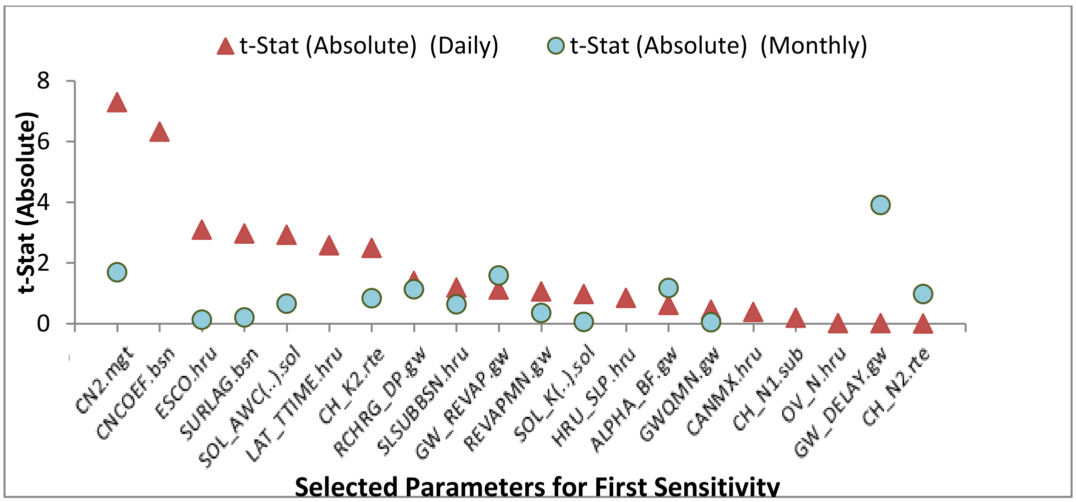

Figure 4-6 - Sensitivity analysis for monthly and daily time step, for Sub-region A1, Gauge Station 4

4-3.4.7. Monthly Calibration and Validation

Since we were going to follow it by daily calibration, the main goals of the monthly calibration were to adjust the volumes and improve the major differences between the observed and simulated hydrographs. Because the results from the manual calibration and model adjustments presented in section 4-3.4.6 were already good, with NSE values of 0.86, 0.65 and 0.84 and bR^2 values of 0.82, 0.67 and 0.83, for Gauge Station 4 (Sub-region A1), Gauge Station 12 (Region B), and 16 (Region C), respectively, and the main problems observed were similar for the three gauges, it was decided to perform one overall calibration for the entire watershed and to only adjust a few parameters.

Some of the peaks were being overestimated, and the simulated recession curves did not match those observed. Figure 4-7 illustrates the differences between observed values and simulated values in hydrographs of 15-month periods for two gauge stations. From this information, as well as the monthly sensitivity analysis shown in Figure 4-6, it was decided to calibrate the two most sensitive parameters: GW_Delay and CN2. The point of calibrating GW_Delay was to attenuate the difference in the recession curves of the hydrographs, and CN2 was decreased in order to increase infiltration values and therefore to decrease simulated surface runoff and the peaks. An automated calibration was performed with SUFI-2 for Gauge Station 4. Since the three different areas showed similar behaviors, and we believe that the GW_delay parameter should have similar values for the entire watershed, the calibrated parameters were applied to the entire watershed. The final optimized values were obtained after 100 runs with determined parameter ranges (Table 4-4).

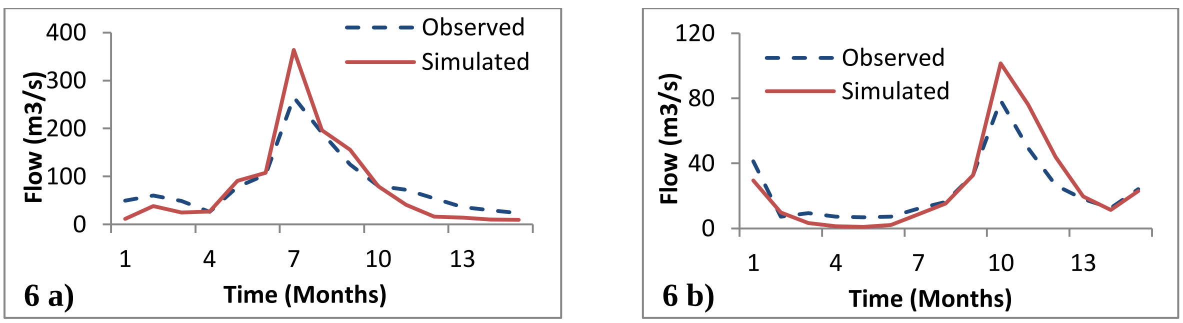

Figure 4-7 - Representative hydrographs of main simulation issues at Gauge Station 12 (a) and at Gauge Station 16 (b)

Table 4-4 Monthly calibrated parameters, ranges and final optimized values

Parameter Change	SWAT Parameter	Calibration Range		Best Final Value
Multiplication to reference value	CN2	0.95	1.05	-0.048%
Addition to reference value	GW-Delay	-15	+50	+49.8

The calibrated and validated flows and performance metrics are presented in figure 8 for Gauge Stations 4, 12 and 16 from the defined Regions A, B and C, respectively. The results were considered good for monthly calibration and validation; values for all the performance metrics and flow dynamics were represented well, as were the volumes. Based on the general performance ratings and recommended statistics for monthly time step by Moriasi et al.[21], the NSE values were rated as very good (NSE>0.75) for validation and calibration on Gauge Stations 4 and 12 as well as for the calibrated period on Gauge Station 16. The NSE value for the validation period on Gauge Station 16 was rated as good. Based on PBias values, the results were considered satisfactory for validation period on Gauge Stations 4 and 16, good for the calibration period on Gauge Station 12, and very good for the calibration period of Gauge Stations 4 and 16 as well as the validation period for Gauge Station 12. Based on RSR statistics, all validation and calibration results were considered to be very good. After this step, daily sensitivity analysis, calibration, validation and cross-validation processes were conducted for refinement of the model simulation (Sections 4-2.7 to 4-2.10).

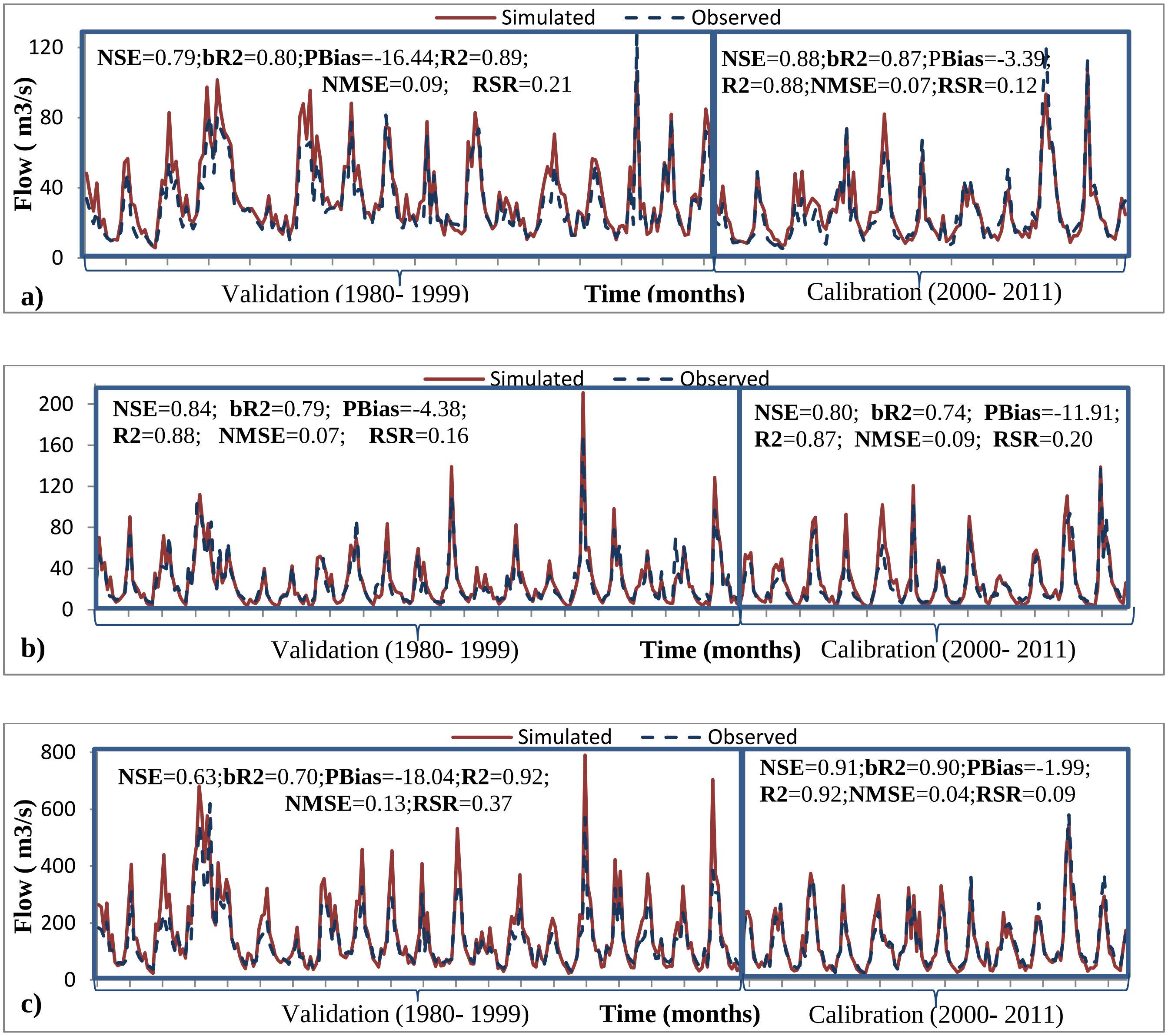

Figure 4-8 - Validated, calibrated and observed flows at monthly time step and performance metrics for Region A, at Gauge Station 4 (a), for Region B, at Gauge Station 12 (b) and at Region C, at Gauge Station 16 (c)

4-3.4.8. Daily Sensitivity Analysis

Before starting daily calibration, a new global sensitivity analysis was done (Figure 4-6) to better understand which parameter changes cause the greatest variability in model output and to identify the most promising parameters to calibrate. Sensitivity analyses were carried out for the Gauge Station 4 for daily and monthly time steps. For the daily time step, different sensitivity analyses were done for every iteration on each one of the three defined regions/gauges. In Figure 4-6 the most sensitive daily parameter is on the left, and the progression is shown up to the least sensitive parameter on the right. The first four most sensitive parameters are CN2, CNCOEF, ESCO and SURLAG, in descending order.

4-3.4.9. Daily Calibration

The calibration results from Regions A and B affect Region C. We decided to start the calibration for Region A of the watershed at Gauge Station 4, because it is an upstream area and should be calibrated before Region C. At the same time, the hypotheses of parameter transfer for the area needed to be tested. In Region A only one sub-region would be calibrated (A1), and the same calibrated parameters would be applied to the other sub-regions (A2 and A3) (Figure 4-3). Going from the monthly calibrated model to a daily time step evaluation, the performance statistics decreased considerably. Negative values for NSE were obtained, as well as values below 0.40 for R^2 and bR^2. However, PBias values were considered good, reinforcing that major volumes were calibrated in the previous step.

The simulated peaks were being overestimated, and the timing of the hydrograph needed to be adjusted as the hydrographs should be attenuated and with a longer recession curve. These aspects of the hydrographs were examined, and sensitivity analysis was studied. To decrease the peaks, for example, we could decrease CN2 or increase the SOL_AWC (Soil Available Water Capacity). Considering that CN2 values had already been decreased almost 5%, which was the threshold that we were willing to change them, and we did not have much more information on the soil properties beyond the ones that were included on the model, it was decided to test SWAT's other method of calculating CN2 rather than to adjust the soil parameter or CN2 values. SWAT's default method of calculating CN2 is as a function of soil moisture, but from this point on, we calculated it as a function of plant evapotranspiration. This made our model, and CN2, more dependent on the previous meteorological conditions than on soil parameters. The method of calculating CN2 as a function of plant evapotranspiration uses a weighting coefficient to calculate the retention coefficient, CNCOEF, which was the second most sensitive parameter in the sensitivity analysis, so it was decided to calibrate this parameter. Also, since this area has considerable forests and a tropical climate, an increase of the maximum canopy (CANMX) intersection for the forests and tree crops was conducted. Although this parameter was not considered very sensitive (Figure 4-6), we considered that it should be further explored.

To deal with the timing of the streamflow hydrographs and make them smoother, it was decided to calibrate the very sensitive parameters, SURLAG and LAT_TTIME. SURLAG is a surface runoff storage feature to lag a portion of surface runoff to the main channel, and LAT_TTIME is the lateral flow travel time. ESCO is another sensitive parameter that we could have explored, but since our previous manual change of this parameter yielded reasonable values for ET and PET we decided not to change it at this point. After these parameters were defined, a few simulations were done on SWAT-CUP in order to see how the changes in SURLAG and LAT_TTIME affected model performance. This local sensitivity analysis was also carried out to see if clear behavior could be observed (linear, polynomial, logarithmic, etc). A few simulations with each parameter were run, and the graphs of the four determined parameters (CNCOEF, CANMAX, SURLAG, LAT_TTIME) and NSE values are shown in Figure 4-9.

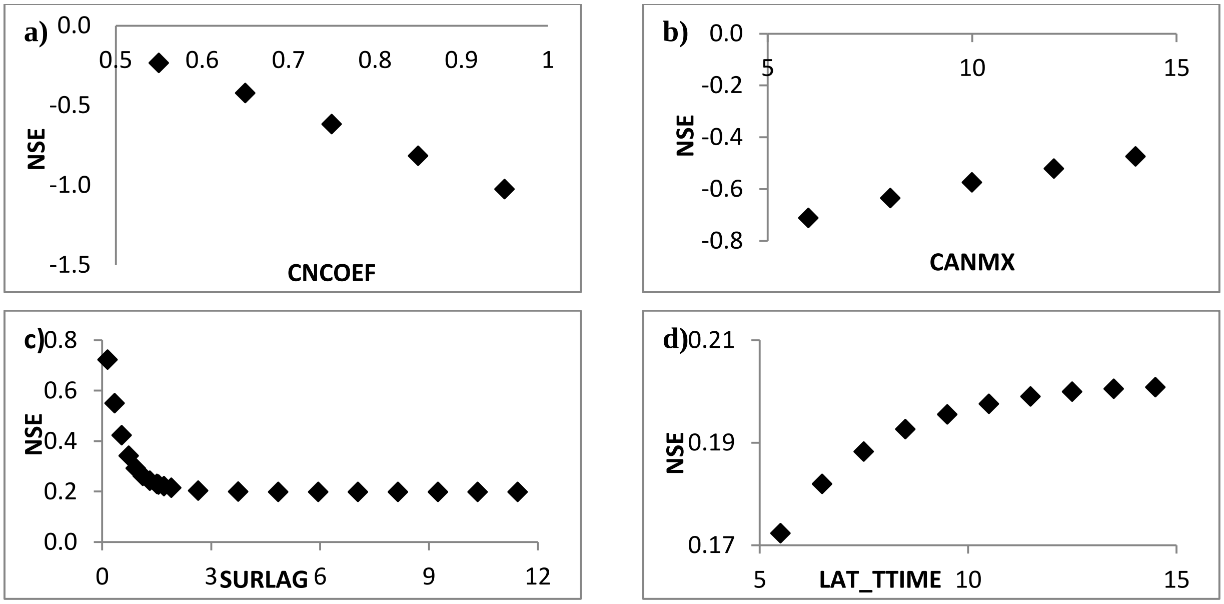

Figure 4-9 - NSE (*Nash-Sutcliffe*) variations based on parameter changes for CNCOEF (a), CANMX (b), SURLAG (c), and LAT_TTIME (d)

Figure 4-9 illustrates clear patterns. CNCOEF has a big impact on NSE model performance metrics, with an almost linear relationship. The best values of model performance occurred when CNCOEF was closer to 0.5 and CANMX was closer to 15. As for SURLAG (for which there is a high variation on NSE values) and LAT_TTIME, the curves' behaviors are closer to logarithmical. The SURLAG curve is a logarithmically decreasing curve, and LAT_TTIME is shown by a logarithmic growth curve. With this information, the ranges were changed for auto-calibration of a few parameters. The CNCOEF range was decreased and set from 0.5 to 0.6. The CANMX parameter was set as from 12 to 15, and the SURLAG range was set between 0.05 and 0.5. The LAT_TTIME range was set between 12 and 15, and also the established end bounds were tested. To better adjust the previously established parameters in the monthly calibration, including GW_Delay, CN2 and ESCO, their ranges were shortened (GW_Delay was set as 80-100, CN2 was set as -4% to -5%, and ESCO was set as 0.68-0.80). In addition, SLSUBBSN (average slope length) was calibrated. The calibrated and observed flows for Gauge Station 4 are shown in Figure 4-10-a (and zoom in at 10-d for one year period), and the calibrated parameters are presented in Table 4-5 and Table 4-6. These parameters were extended to the defined sub-regions with similar characteristics in Region A.

Other than CNCOEFF all the other parameters will not change the previously calibrated model at monthly time step, but only change the shape of the hydrology in terms of timing of raise to the peak and recession curve, which was the focus of the daily calibration. This parameter was not considered at the monthly calibration. Region A is more dominated by forest, so the canopy interception and water infiltration are high and most of the flow is dominated by base flow than surface flow. Therefore the CN calculation based on plant ET method worked much better than based on the soil ET method (at region A, Figure 4-9). However if the watershed is dominated by agriculture or urban, where the ground is covered partially, then soil ET method may work better. Although looking at the different regions within the watershed (A, B and C) the pathways of water movement/hydrology are different. Since in the current version of the SWAT model, the CN calculation as a function of plant evapotranspiration (ET) method is available only at watershed level, and not on subbasin level, during the calibration of region A, the CNCOEFF was set to the entire watershed.

The second stage was to calibrate Region B at Gauge Station 12. Considering that watershed wide parameter changes from the calibration of Sub-region A1 would affect the results for Region B, the model performance for Region B was assessed using the calibrated parameters defined for Sub-region A1. The results were already found to be satisfactory, with a NSE value close to 0.55. However, there was a need to better adapt to the conditions of this region, which has different distributions of land uses and slopes, as well as base flow and groundwater characteristics. The groundwater related parameters were calibrated, as well as the RCHRG_DP (recharge to deep aquifer) and the OV_N (manning's "n" value for overland flow), which showed to be sensitive parameters for this area. SUFI-2 was run for two iterations, the first with 200 runs and the second with 50. The final calibrated values can be found in Table 4-5 and Table 4-6, and the simulated and calibrated flows are shown in Figure 4-10 -b, with related performance metrics.

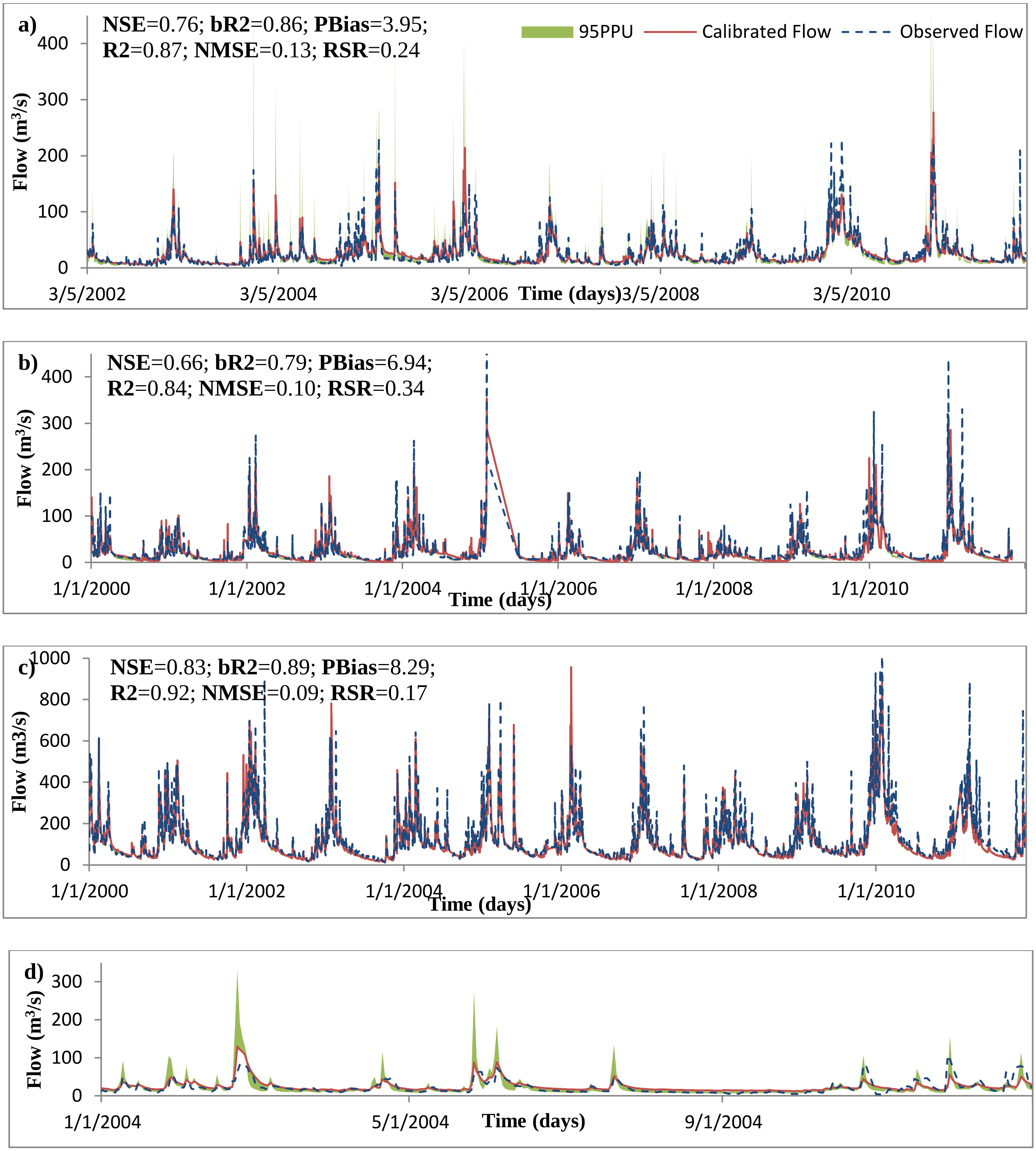

Figure 4-10 - Calibrated and observed flows at a daily time scale, uncertainty bands and performance metrics for Sub-region A1, at Gauge Station 4 (a), for Region B, at Gauge Station 12 (b) and for Region C, at Gauge Station 16 (c), and a zoom in for a one year period for Gauge Station 4 (d)

The third stage was to adjust the calibrated parameters for Regions A and B in the SWAT model, and then to calibrate the most downstream gauge of the watershed: Gauge Station 16. The region is composed of lowlands, with less forest and less dense vegetation. First a sensitivity analysis was performed, and then a SUFI-2 iteration with 150 runs was carried out. The calibrated parameters are shown in Table 4-5 and Table 4-6. The parameters were applied for the entire Region C, and the calibrated and simulated flows and performance criteria for C are shown in Figure 4-10-c.

The performance metrics were statistically considered good, as was the visual comparison on the hydrographs between the simulated, calibrated flow and the observed flow for the three gauge stations. NSE values were all above 0.65, PBias values were between 0 and 10, bR^2 and R^2 values were all superior to 0.79, NMSE were smaller than 0.15, and RSR were smaller than 0.35. The model performance criteria from Moriasi et al[21] for a monthly time step, here being applied to a daily time step, rate the results as good and very good based on NSE, and very good based on PBias and RSR. The calibrated final parameters and changes made to the model are shown in Table 4-5 for the entire watershed and in Table 6 for the regions. As expected, there are different parameter values for A1, B and C. Some examples of variances include the parameters related to ground water and base flow (such as GW_DELAY, GW_REVAP, REVAPMN, RCHRG_DP, GWQMN, and ALPHA_BF). One of the most sensitive and uncertain parameters for daily calibration, SURLAG, had small calibrated value. This was adjusted with the slope and Manning 'n', since the friction coefficient changed with variances in forest cover and slope along the watershed. Also, there were changes in CANMX and LAT_TTIME, as expected, and in CN2.

Table 4-5 Calibrated changes and SWAT default values for the entire watershed

Parameter	Description	Default value	Calibrated value
IPET	Potential evapotranspiration method	Penman-Monteith	Priestley-Taylor
ESCO	Soil evaporation compensation factor	0.95	0.75
ICN	Daily curve number calculation method	Soil moisture	Plant ET
CNCOEF	Plant ET curve number coefficient	1	0.5
SURLAG	Surface runoff lag time (days)	4	0.086
SLSUBBSN	Average slope length (m)	-	-4.15%
SHALLST	Initial depth of water in shallow aquifer (mm)	0.5	4,000
DEEPST	Initial depth of water in deep aquifer (mm)	1000	10,000

Table 4-6 Parameter calibration changes and SWAT default values for the three selected regions (A, B, C)

Parameter	Description	Default	A	B	C
GW_DELAY	Groundwater delay time (days)	31	95	95	93.23
GW_REVAP	Groundwater "revap" coefficient	0.02	0.02*	0.03	0.07
REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	1	3500	3500	3425
RCHRG_DP	Deep aquifer percolation fraction	0.05	0.05*	0.08	0.1
GWQMN	Threshold depth of water in the shallow aquifer for return flow to occur (mm)	0	3000	3883.33	3123.33
LAT_TTIME	Lateral flow travel time (days)	0	15	0.4	2.33
CANMX	Maximum canopy storage (mm)	0	15	15	0
CN2	SCS curve number (moisture condition II)	-	-4.50%	-3.62%	4.00%
OV_N	Manning's "n" value for overland flow	-	*	-7.67%	*

*-Parameters not calibrated, default values used.

4-3.4.10. Validation

Validation was performed for 1980-1999 (20 years) for the three calibrated gauge stations (4, 12 and 16). The validation results (Table 4-7) were considered statistically good and similar to the ones from the calibration period, showing robustness in the model for the 30 year period in which it simulated. NSE values were above 0.65, RMSE values were smaller than 20 for Gauge Stations 4 and 12, but closer to 70 on Gauge Station 16, which was considerable normal since it has the largest drainage area and flow volumes. The bR2 values were greater than 0.70, R2 were greater than 0.85, absolute PBias values were smaller than 15, NMSE values were smaller than 0.20, and RSR values were smaller than 0.35. Results (NSE, RSR, and PBias) were considered to be good and very good, when assessed based on the Moriasi et al. (2007) model performance criteria.

Table 4-7 Daily validation performance metrics

Gauge station	Drainage area (km^2)	NSE	RMSE	bR2	R2	PBias	NMSE	RSR
4	2,308	0.80	11.06	0.82	0.92	-7.57	0.09	0.20
12	1,581	0.70	16.74	0.81	0.85	5.75	0.16	0.30
16	11,040	0.67	66.45	0.73	0.94	-12.80	0.12	0.33

4-3.4.11. Cross-Validation

A Cross-validation for 13 gauge stations with good available data in the watershedFigure 4-2) was performed for the entire period (for the stations which had data). The results for all of the gauge stations (Table 4-8) suggest that the calibrated parameters provide a good simulation of the entire watershed for the more than 30 year period. All NSE values were above 0.65; bR2 and R2 were greater than 0.69; absolute PBias values were smaller than 16; NMSE values were not greater than 0.20; and RSR was less than 0.35. Applying the calibrated parameters from Sub-region A1 to A2 and A3 yielded good statistical results and validated the selection of the three different regions (A, B, C) for calibration.

Table 4-8 Cross-validation daily performance metrics for the entire simulation period (1980-2011)

Gauge station	Drainage area (km^2)	NSE	bR2	R2	PBias	NMSE	RSR
1*	1143	0.65	0.79	0.84	15.81	0	0.35
2	1920	0.80	0.88	0.90	5.49	0.11	0.20
3*	2152	0.75	0.86	0.88	9.58	0.13	0.25
5	1950	0.79	0.85	0.91	1.94	0.11	0.21
6	1140	0.75	0.82	0.87	-1.65	0.13	0.25
7*	1950	0.78	0.86	0.88	4.82	0.12	0.22
8	2180	0.69	0.83	0.83	-3.52	0.17	0.31
9*	2187	0.86	0.69	0.73	-2.34	0.07	0.14
10	387	0.66	0.76	0.86	-0.65	0.13	0.34
11	928	0.72	0.78	0.88	-1.88	0.13	0.28
13*	4045	0.79	0.83	0.91	1.36	0.09	0.21
14*	7327	0.83	0.88	0.91	8.61	0.09	0.17
15*	8500	0.83	0.86	0.92	14.61	0.09	0.17

*- These gauge stations had data only for the calibration period (2000-2011)

4.3.4.12. Uncertainty Analysis

Since many models and parameter sets may yield good fits of simulated to observed data, the uncertainty was also addressed using the concept of equifinality of models (Beven, 2006). The calibration goal, is to obtain better statistical values, for NSE, RSR and PBias, etc, while maintaining *P* and *R-factors* and uncertainty of inputs within reasonable range. Any value within this uncertainty band would be an acceptable model. Therefore, the input and parameter uncertainties were assessed by looking at the calibrated parameter ranges that provided an acceptable simulation (within the 95% prediction uncertainty bands), according to the model evaluation guidelines suggested by Moriasi et al.[21] for monthly time-step, applied here for daily time-step. Model output uncertainty was assessed by looking at model output for two different situations: high flows and base flows. High flows and base flows were estimated through the Baseflow Filter Program [93,143] for observed and simulated flows. The model output uncertainty was also assessed using the 95% prediction uncertainty band with the acceptable fits (described in section 3.3), as well as an assessment of flow duration curves with 95% prediction uncertainty bands as a measure of model output confidence.

The uncertainties of the parameter ranges are presented in box-plots in Figure 4-11. The first letter before the parameter relates to how the parameter was changed, as well as what is presented. An R indicates a relative change (percentage), V replaces the value of the parameter, and A is an addition (adding to SWAT's default value).

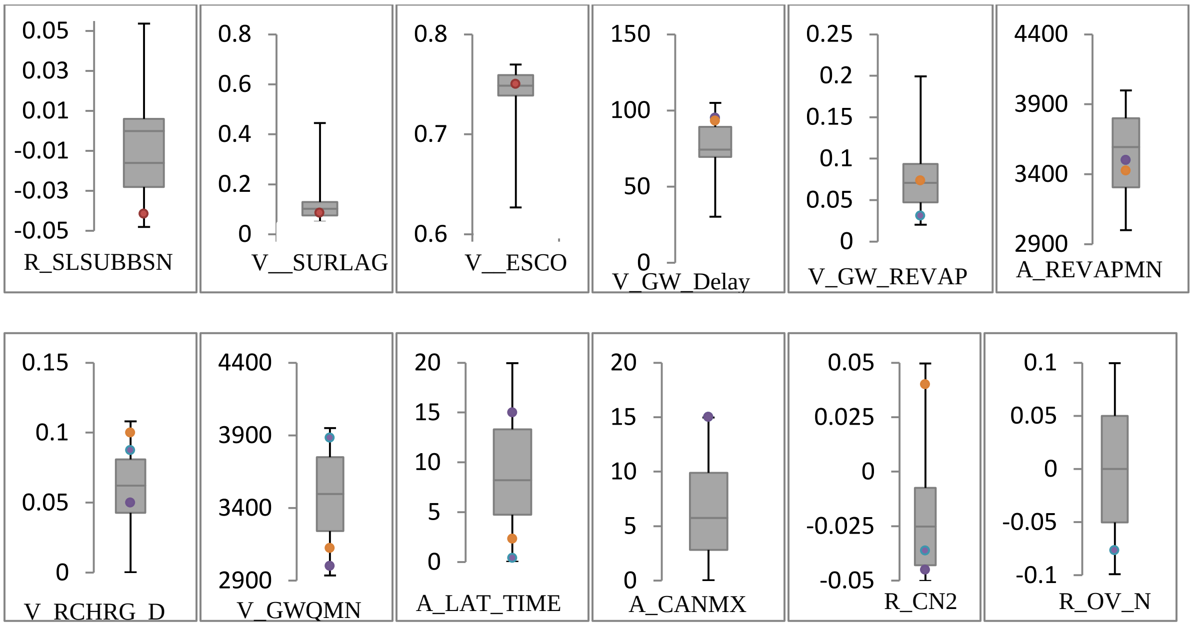

Figure 4-11 - Box-plot of parameter uncertainty ranges for the three regions. The calibrated parameters are represented as dots (Red are the watershed scale parameter, Purple for region A, Blue for region B, and Orange for region C).

The box-plots presented in Figure 4-11 provide a visual understanding of the uncertainty associated with the model inputs. Acceptable parameter ranges and the calibrated parameters are shown for all the calibrated parameters for all the calibration runs conducted for the three regions. For a few parameters, including SURLAG and ESCO, we can see a small spread around the median, a small range of variability and, therefore, less parameter uncertainty. This representation also provides the entire range of parameters that demonstrated satisfactory simulation results (with NSE values equal to or greater than 0.5). These demonstrate the non-uniqueness of the calibration process, the model input uncertainties (parameters), as well as equifinality concept [144], considering that different combinations of parameters in the acceptable ranges could have provided satisfactory or even better simulation results.

The 95% prediction uncertainty band was shown in Figure 4-10, for the three gauge stations where flow was calibrated. In the first calibration site, Gauge Station 4 of Sub-region A1, the uncertainty is higher, since some watershed parameters were defined in this step of the calibration (Figure 4-10 - a and -d). For a comprehensive graphical view of the calibration and predicted uncertainty bands, flow-duration curves (FDCs) representing magnitude and frequency of daily flows for the period are presented in Figure 4-12. These FDCs have several applications in water resources management; they provide an estimate of percentage of time in which a given streamflow was equaled or exceeded. The calibrated model results demonstrated a good fit to observed flows for the time period. Figure 4-12 also depicts the related uncertainty bands.

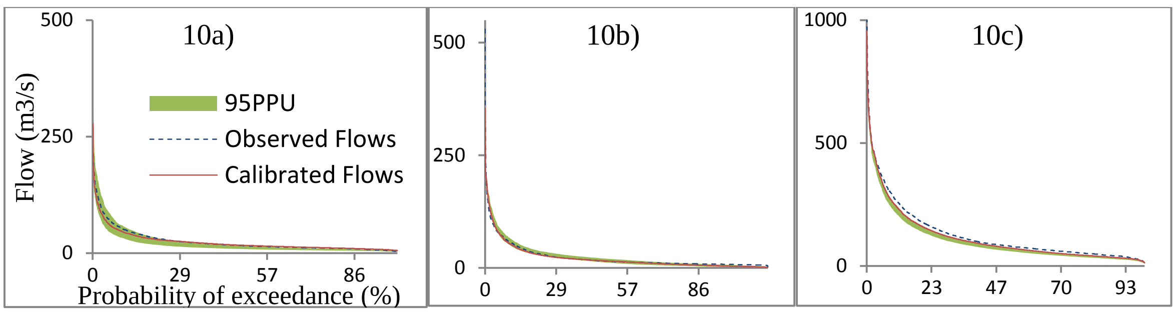

Figure 4-12 - Flow duration curves for simulated and observed flows for Gauge Stations 4 (a), 12 (b) and 16 (c)

presents the performance metrics (NSE, BR2 and PBias) for five gauge stations within the watershed for the calibration period to access model output uncertainty assessed by analyzing the model performances for base flows and high flows.

Table 4-9 Model perfomance metrics for daily base flow and high flow for five selected gauge stations

Gauge	Drainage		Base flow			High flow	
station	area (km^2)	NSE	BR2	PBias	NSE	BR2	PBias
4	2308	0.77	0.78	-14.01	0.57	0.75	30.25
7	1950	0.63	0.81	-7.01	0.69	0.69	27.53
12	1581	0.50	0.69	-9.50	0.55	0.66	2.74
14	7327	0.89	0.91	-1.74	0.68	0.79	26.19
16	11040	0.89	0.92	0.86	0.72	0.79	21.02

For the five gauge stations, the different performance metrics for both high flow and base flow were consistent and considered to be satisfactorily simulated according to the statistical criteria. Base flow has higher NSE values for almost all gauge stations than high flow. Base flow NSE values are all above 0.50, and for some of the more downstream gauges (14 and 16) of the watershed values are close to 0.90. Base flow also has good BR2 values, all above 0.69, and low PBias absolute values, all smaller than 15. The high flows results were also considered satisfactory, but the model output confidence is less overall, with smaller overall NSE and BR2 values, and larger absolute PBias values. The uncertainty in high flows can also be attributed to measured data uncertainty, since for high flow episodes the rating curves are frequently extrapolated.

4-5. Conclusions

We proposed a step-by-step, systematic approach to calibrating and validating hydrological modeling in specific to flow simulations. This approach includes sensitivity analysis, calibration, validation, and uncertainty analysis procedures and takes into account the majority of the water flow processes that occur in the watershed. This knowledge and other available information are incorporated into each step of the model calibration. We believe that the systematic approach presented here can help modelers in their own projects for their particular goals. We described key elements and literature for each topic that was considered important for the calibration/validation of a watershed model for flow, presenting an overall discussion and recommendations. The main point that we would like to get across is that calibration can be performed in a variety of ways that may lead to acceptable results, but available information and knoweledge of the watershed should be incorporated into the calibration so as to try to represent well the processes of the particular watershed; not only to obtain good and limited (such as NSE and R2) statistical results.

A case study of this methodology was presented for a complex watershed, and the results and discussion were presented for each step. The Piracicaba watershed systematic calibration results demonstrated the importance of all the steps defined in the systematic calibration procedure in section 4-2. Also the results demonstrated the importance of the incorporation of the main processes and available data into the calibration procedure, such as different potential evapotranspiration, comparison with remote sensing data for ET, crop yield, canopy interception, base flow, high flows, and overall watershed dynamics, monthly and then daily dynamics. Calibration, validation and cross-validation presented good performance metrics for all analyzed gauge stations. An uncertainty analysis was undertaken for the model inputs and outputs, demonstrating uncertainties related to the input parameters with 95% prediction uncertainty bands (95 PPU). This uncertainty analysis showed the non-uniqueness of calibration results, base flow and high flow simulations, and flow duration curves. These suggested confidence for model results and 95% prediction uncertainty bands (95 PPU).

4-6. Acknowledgements

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4-7. References

1 - Arnold, JG; Youssef, MA; Yen, H ; White, MJ.; Sheshukov, AY; Sadeghi, AM; Moriasi, DN; Steiner, JL.; Amatya, DM; Skaggs, RW; Haney, EB.; Jeong, J; Arabi, M; Gowda, PH. 2015. Hydrological Processes and Model Representation: impact of soft data on calibration. Journal of ASABE. “In Press”.

2 - Gupta, HV, Sorooshian, S, Yapo, P, Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. Journal of Hydrologic Engineering, Reston, 1999. 4(2), 135-143.

3 - Gupta, HV, Perrin, C, Bloschl, G, Montanari, A, Kumar, R, Clark, M, Andréassian, V. Large-sample hydrology: a need to balance depth with breadth. Hydrology and Earth System Sciences, Copernicus Publications, 2014, 18 (2), 463 -477.

4 - Muleta, MK, Nicklow, JW. Sensitivity and uncertainty analysis coupled with automatic calibration for a distributed watershed model. *J Hydrol;* 2004, 306(1–4), 127–145.

5 - Kirchner, JW. Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology. Water Resour. Res., 2006, 42, W03S04, doi:10.1029/2005WR004362.

6 - Seibert, J, McDonnel, JJ. On the dialog between experimentalist and modeler in catchment hydrology: Use of soft data for multicriteria model calibration. Water Resour. Res., 2002, 38 (11), W03S04, doi: 10.1029/2001WR000978.

7 - Jakeman, AJ, Letcher, RA, Norton, JP, Ten iterative steps in development and evaluation of environmental models. Environmental Modelling & Software, 200621 (5), 602-614, ISSN 1364-8152, doi:10.1016/j.envsoft.2006.01.004.

8 - Pitt, MA, Myung, IJ. When a good fit can be bad. TRENDS in Cognitive Sciences, 20026(10).

9 - Reichert, P, Omlin, M . On the usefulness of overparameterized ecological models. Ecological Modelling, 1997, 95 (1997), 289-299.

10 - Yen, H, Bailey, RT, Arabi, M, Ahmadi, M, White, MJ, Arnold, JG. The Role of Interior Watershed Processes in Improving Parameter Estimation and Performance of Watershed Models. Journal of Environmental Quality, 2014. 43,1601–1613. doi:10.2134/jeq2013.03.0110

11 - Beven, K.. A manifesto for the equifinality thesis. Journal of Hydrology, 2006. 320(1–2), 18-36. doi: 10.1016/j.jhydrol.2005.07.007.

12 - Borah, DK; Bera M, Watershed-scale hydrologic and nonpoint-source pollution models: review of applications. Transactions of the ASAE. 2004. 47(3), 789-803. doi: 10.13031/2013.16110.

13 - Daniel E B, Camp J V, LeBoeuf E J, Penrod J R, Dobbins J P, Abkowitz M D. Watershed Modeling and its Applications: A State-of-the-Art Review. The Open Hydrology Journal. 2011; 5, 26-50. doi: 10.2174/1874378101105010026.

14 -Singh, VP; Woolhiser, DA. Mathematical modeling of watershed hydrology. Journal of Hydrologic Engineering. 20027(4), 270-292. doi: 10.1061/(ASCE)1084-0699(2002)7:4(270).

15 - Arnold, JG, Srinivasan, R, Muttiah, RS., Williams, JR, Large-area hydrologic modeling and assessment: Part I. Model development. J. American Water Resour. Assoc. 1998. 34(1), 73-89.

16 - Arnold, JG, Fohrer, N, SWAT2000: Current capabilities and research opportunities in applied watershed modeling. Hydrol. Process, 2005. 19(3): 563-572.

17 - Bressiani, DA, Gassman, PW, Fernandes, JG, Garbossa, LHP, Srinivasan, R, Mendiondo, EM Bonumá, N B, A review of SWAT (Soil and Water Assessment Tool) applications in Brazil: challenges and prospects. Int J Agric & Biol Eng, 2015; 8(3): 9—35.

18 - Gassman, PW, Reyes, MR, Green, CH, Arnold, JG, The soil and water assessment tool: Historical development, applications, and future research directions. *Transactions ASAE*. 2007. 50(4), 1211–1250.

19 - Williams, JR, Arnold, JG, Kiniry, JR, Gassman, PW, Green, CH. History of model development at Temple, Texas. Hydrol. Sci. 200853(5), 948-960.

20 - Douglas-Mankin, KR, Srinivasan, R, Arnold, JG, Soil and Water Assessment Tool (SWAT) model: Current Developments and Applications. Transactions of the ASABE, 2010.. 53(5), 1423-1431.

21 - Moriasi D, Arnold JG, Van Liew MW, Bingner R, Harmel R, Veith TL. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE 50, 2007, 885-900. doi: http://ddr.nal.usda.gov/handle/10113/9298.

22 - White, KL; Chaubey, I. Sensitivity Analysis, Calibration, and Validations for a Multisite and Multivariable SWAT Model. Journal of the American Water Resources Association *(JAWRA)*. 2005. 41(5),1077-1089.

23 - Arnold, JG, Moriasi, DN., Gassman, PW., Abbaspour, KC., White, MJ., Srinivasan, R, Santhi, C, Harmel, RD., van Griensven, A, Van Liew, MW, Kannan, N, Jha, MK, SWAT: model use, calibration, and validation. Trans. ASABE. 2012. 55(4), 1491-1508. doi: 10.13031/2013.42256.

24 - Arnold, J. G., Kiniry, J. R., Srinivasan, R., Williams, J. R., Haney, E. B., Neitsch, S. L. Soil and Water Assessment Tool Input/Output Documentation, Version 2012. Texas Water Resources Institute. 2012. TR-439. Availabe at: http://swat.tamu.edu/media/69296/SWAT-IO-Documentation-2012.pdf.

25 - Neitsch SL, Arnold JG, Kiniry JR, Williams JR. Soil and Water Assessment Tool Theoretical Documentation: Version 2009. Temple, TX: Grassland, Soil and Water Research Laboratory, Agricultural Research Service. 2011. Available: www.brc.tamus.edu/swat/doc.html. Accessed on: [2013-07-10].

26 - Gupta, HV, Sorooshian, S, Yapo, PO, Toward improved calibration of hydrologic models: multiple and non-commensurable measures of information. Water Resour. Res. 1998. 34(4), 751-763.

27 - Shafii, M, Smedt, F De., Multi-objective calibration of a distributed hydrological model (WetSpa) using genetic algorithm. Hydrol. Earth Syst. Sci., 2009. 13, 2137-2149.

28 - Efstratiadis, A, Koutsoyiannis, D. One decade of multi-objective calibration approaches in hydrological modelling: a review. Hydrol. Sci. J. 2010. 55(1), 58-78.

29 - Ahmadi, M, Ascough II, JC, DeJonge, KC, Arabi, M. Multisite-multivariable sensitivity analysis of distributed watershed models: Enhancing the perceptions from computationally frugal methods. Ecological Modelling. 2014, 279, 54-67.

30 - Meixner, T, Bastidas, LA, Gupta, HV, Bales, RC. Multicriteria parameter estimation for models of stream chemical composition. Water Resour Res. 2002. 38(3), 9-1-9-9. 10.1029/2000WR000112.

31 - Zhang, X, Srinivasan, R, GIS-Based Spatial Precipitation Estimation: A Comparison of Geostatistical Approaches. Journal of the American Water Resources Association (JAWRA), 2009. 45(4), 894-906. doi:10.1111/j.1752-1688.2009.00335.x.

32 - Abbaspour, KC, Yang, J, Maximov, I, Siber, R, Bogner, K, Mieleitner, J, Zobrist, J, Srinivasan, R, Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. Journal of Hydrology. 2007. 333, 413-430.

33 - Bilondi, MP, Abbaspour; KC, Ghahraman, B. Application of three different calibration-uncertainty analysis methods in a semi-distributed rainfall-runoff model application. Middle-East Journal of Scientific Research. 2013. 15(9), 1255-1263 . doi: 10.5829/idosi.mejsr.2013.15.9.11470

34 - Kim, SM, Benham, BL, Brannan, KM, Zeckoski, RW and Doherty, J. Comparison of hydrologic calibration of HSPF using automatic and manual methods, Water Resour. Res., 2007. 43, W01402, doi:10.1029/2006WR004883.

35 - Madsen, H, Wilson, G, and Ammentorp, HC, Comparison of different automated strategies for calibration of rainfall-runoff models, J. Hydrol., 2002, 261, 48 – 59.

36 - Wu, Y; Liu, S. Automating calibration, sensitivity and uncertainty analysis of complex models using the R package Flexible Modeling Environment (FME): SWAT as an example. Journal Environmental Modelling & Software, 2012, 31, 99-109, doi: 10.1016/j.envsoft.2011.11.013.

37 - Yang, J, Reichert, P, Abbaspour, KC, Xia, J, Yang, H. Comparing uncertainty analysis techniques for a SWAT application to the Chaohe Basin in China. Journal of Hydrology, 2008. 358, 1-23. doi: 10.1016/j.jhydrol.2008.05.012

38 - Balascio, CC, Palmeri DJ, Gao H. Use of a genetic algorithm and multi-objective programming for calibration of a hydrologic model. Trans. ASAE, 1998. 41(3): 615-619.

39 - Van Liew, MW, Arnold, JG and Bosch, DD. Problems and potential of autocalibrating a hydrologic model. Trans. ASAE . 2005, 48(3): 1025-1040.

40 - Boyle, DP; Gupta, HV; Sorooshian, S. Toward improved calibration of hydrologic models: Combining the strengths of manual and automatic methods. Water Resources Research. 2000 36(12), 1944-7973. doi: 10.1029/2000WR900207

41 - Doherty, J, Johnston, JM, Methodologies for calibration and predictive analysis of a watershed model. Journal of the American Water Resources Association. 2003. 39(2):251-265.

42 - Christensen, S, and Doherty, J. Predictive error dependencies when using pilot points and singular value decomposition in groundwater model calibration. Advances in Water Resources. 2008, 31, 674-700.

43 - Govender, M, Everson, CS. Modelling streamflow from two small South African experimental catchments using the SWAT model. Hydrol. Proc. 200519(3): 683-692.

44 - Ng, TL, Eheart, JW, Cai, XM. Comparative calibration of a complex hydrologic model by stochastic methods GLUE and PEST. Trans ASABE, 2010, 53, 1773–1786.

45 - Wang, X, Melesse, AM, Evaluation of the SWAT model's snowmelt hydrology in a northwestern Minnesota watershed. Trans. ASAE, 2005. 48(4): 1359-1376.

46 - Abbaspour, KC, SWAT-CUP4: SWAT Calibration and Uncertainty Programs - A User Manual. © Eawag, 2011. Available: http://www.eawag.ch/forschung/ siam/software/swat/index_EN. Accessed on: 2013-05-13.

47 - Wu, Y; Liu, S. Automating calibration, sensitivity and uncertainty analysis of complex models using the R package Flexible Modeling Environment (FME): SWAT as an example. Journal Environmental Modelling & Software, 2012. 31, 99-109, doi: 10.1016/j.envsoft.2011.11.013.

48 - Wu, Y, Liu, S, Improvement of the R-SWAT-FME framework to support multiple variables and multi-objective functions. Science of The Total Environment, 2014, 466–467, 455-466, doi: 10.1016/j.scitotenv.2013.07.048.

49 - van Griensven, A, Bauwens, W, Multiobjective autocalibration for semidistributed water quality models. Water Resour. Res. 2003. 39(12): 1348-1356.

50 - van Griensven, A, Bauwens W. Application and evaluation of ESWAT on the Dender basin and Wister Lake basin. Hydrol. Proc. 2005 19(3): 827-838.

51 - Akhavan, S, Abedi-Koupai, J, Mousavi, SF., Afyuni, M, Eslamian, SS, Abbaspour, KC, Application of SWAT model to investigate nitrate leaching in Hamadan-Bahar watershed, Iran. J. Agric. Ecosystem and Environ. 2010. 139(4), 675-688.

52 - Anderson, MC; Kustas, WP; Norman, JM.; Hain, CR; Mecikalski, JR; Schultz, L; González-Dugo, MP; Cammalleri, C; d'Urso, G; Pimstein, A; Gao, F. 2011. Mapping daily evapotranspiration at field to continental scales using geostationary and polar orbiting satellite imagery. Hydrology and Earth System Sciences. 15 (1), 223-239. doi: 10.5194/hess-15-223-2011.

53 - Faramarzi, M, Abbaspour, KC, Schulin, R, Yang, H,. Modeling blue and green water availability in Iran. Hydrol. Proc. 2009, 23(3), 486-501.

54 - Rodrigues, DBB, Gupta, HV, Mendiondo, EM. A blue/green water-based accounting framework for assessment of water security. Water Resour. Res. 2014, 50, 7187–7205. doi:10.1002/2013WR014274

55 - Schuol, J, Abbaspour, KC, Srinivasan, R, Yang, H, Estimation of freshwater availability in the west African subcontinent using the SWAT hydrologic model. J. Hydrol. 2008. 352(1-2), 30-49.

56 - Nash, JE, Sutcliffe, JV. River flow forecasting through conceptual models: Part 1. A discussion of principles. J. Hydrology, 1970. 10(3): 282-290.

57 - Krause, P, Boyle DP, Base F. Comparison of different efficiency criteria for hydrological model assessment. Advances in Geosciences, 2005. 5, 89-97. doi:10.5194/adgeo-5-89-2005.

58 - Price, K, Purucker, ST, Kraemer, SR, Babendreier, JE, Tradeoffs among watershed model calibration targets for parameter estimation, Water Resour. Res, 2012, 48, W10542, doi:10.1029/2012WR012005.

59 - Wang, Z, Batelaan, O, De Smedt, F: A distributed model for Water and Energy Transfer between Soil, Plants and Atmosphere (WetSpa), Phys. Chem. Earth, 1997. 21(3), 189–193.

60 - Duan Q, Sorooshian S, Gupta VK. Effective and efficient global optimization for conceptual rainfall–runoff models. Water Resour. Res.,1992. 28, 1015–1031.

61 - Gupta H, Wagener T, Liu Y. Reconciling theory with observations: Elements of a diagnostic approach to model evaluation, Hydrol. Processes, 2008. 22, 3802–3813.

62 - van Griensven A, Meixner T. A global and efficient multi-objective auto-calibration and uncertainty estimation method for water quality catchment models. J. Hydroinformatics, 2007. 09.4, 277-291. doi: 10.2166/hydro.2007.104.

63 - Legates DR, McCabe GJ. Evaluating the use of “goodness-of-fit” Measures in hydrologic and hydroclimatic model validation**.** Water Resour. Res. 1999. 35 (1). doi: 10.1029/1998WR900018

64 - Gupta HV, Kling H. On typical range, sensitivity, and normalization of Mean Squared Error and Nash-Sutcliffe Efficiency type metrics. Water Resour. Res. 2011. 47. Doi: 10.1029/2011WR010962.

65 -Schaefli B, Gupta HV. Do Nash values have value? Hydrological Processes. 2007, 21 (15), 2075-2080

66 - Ávila-Carrasco, R, Mojarro Dávila, F, Moriasi, DN, Gowda, PH, Bautista-Capetillo, C, Echavarria-Cháirez, FG, Garbrecht, JD, Steiner, JL, Howell, TA, Kanemasu, ET, Verser, JA, Wagner, K, Hernandez J. Calibration of SWAT2009 using crop biomass, evapotranspiration, and deep recharge: Calera watershed in Zacatecas, Mexico case study. Journal of Water Resource and Protection. 2012. 4(7),439-450. doi:10.4236/jwarp.2012.47051.

67 - Nair, SS, King, KW, Witter, JD, Sohngen, BL, Fausey, NR. Importance of crop yield in calibrating watershed water quality simulation tools. J. American Water Resources Association. 2011, 47(6): 1285-1297.

68 - White, MJ, Harmel RD, Arnold JG, Williams JR. SWAT Check: A screening tool to assist users in the identification of potential model application problems. Journal of Environmental Quality. 2012. doi:10.2134/jeq2012.0039.

69 - Srinivasan, R, Zhang, X, Arnold, J; SWAT Ungauged: Hydrological budget and crop yield predictions in the upper Mississippi river basin. Trans ASABE. 2010. 53(5), 1533-1546. ISSN 2151-0032.

70 - Nossent J, Bauwens W. Application of a normalized Nash-Sutcliffe efficiency to improve the accuracy of the Sobol’sensitivity analysis of a hydrological model, in: EGU General Assembly Conference Abstracts, 2012. 14, 237.

71 - Sanadhya P, Gironás J, Arabi M. Global sensitivity analysis of hydrologic processes in major snow-dominated mountainous river basins in Colorado. Hydrol. Process. 2014. 28 (9). 3404-3418. Doi: 10.1002/hyp.9896.

72 - van Griensven A, Meixner T, Grunwald S, Bishop T, Diluzio M, Srinivasan R. A global sensitivity analysis tool for the parameters of multi-variable catchment models. 2006. Journal of Hydrology, 324, 10–23. doi:10.1016/j.jhydrol.2005.09.008.

73 - Yilmaz KK, Gupta, HV, Wagener, T. A process-based diagnostic approach to model evaluation: Application to the NWS distributed hydrologic model. Water Resour. Res. 2008. 44, 9. Doi: 10.1029/2007WR006716

74 - Schoups, G, van de Giesen, NC, Savenije, HHG, Model complexity control for hydrologic predictions. Water Resour. Res., 2008, 44, W00B03, doi: 10.1029/2008WR006836.

75 - Cherkassky, V. S., Mulier F. 2007. Learning from data: concepts, theory, and methods. 2nd ed. John Wiley & Sons, Inc., Hoboken, New Jersey. ISBN 978-0-471-68182-3.

76 - Vicens GJ, Rodríguez-Iturbe I, Schaake Jr. JC. Bayesian generation of synthetic streamflows. 1975. 11 (6), 827–838. doi: 10.1029/WR011i006p00827

77 - Butts, MB., Payne, JT., Kristensen, M, Madsen, H; An evaluation of the impact of model structure on hydrological modelling uncertainty for streamflow simulation. Journal of Hydrology. 2004. 298(1–4),242-266.

78 - Harmel, RD, Smith PK; Consideration of measurement uncertainty in the evaluation of goodness-of-fit in hydrologic and water quality modeling. Journal of Hydrology. 2007. 337, 326-336. doi: 10.1016/j.jhydrol.2007.01.043.

79 - Li Z, Shao Q, Xu Z, Cai X. Analysis of parameter uncertainty in semi-distributed hydrological models using bootstrap method: A case study of SWAT model applied to Yingluoxia watershed in northwest China. Journal of Hydrology. 2010. 385(1–4), 76-83, doi:10.1016/j.jhydrol.2010.01.025.

80 - Pappenberger, F.; K. J. Beven. 2006. Ignorance is bliss: Or seven reasons not to use uncertainty analysis, *Water Resour*. Res., 42, W05302, doi:10.1029/2005WR004820.

81 - Wagener, T, McIntyre, N, Lees, MJ, Wheater, HS, Gupta, HV; Towards reduced uncertainty in conceptual rainfall-runoff modelling: dynamic identifiability analysis. Hydrological Processes. 2003. 17(2),doi: 10.1002/hyp.1135

82 - Williams, JR, Flood routing with variable travel time or variable storage coefficients. Trans. ASAE. 1969, 12(1):100-103.

83 - Gassman, PW, Sadeghi, AM, Srinivasan, R, Applications of the SWAT Model Special Section: Overview and Insights. Journal of Environmental Quality, 2014. 43; 1–8. doi: 10.2134/jeq2013.11.0466.

84 - Green, WH, Ampt, GA, Studies on soil physics, 1. The flow of air and water through soils. Journal of Agricultural Sciences. 1911. 4, 11-24.

85 - USDA-SCS, Soil Conservation Service. 1972. Section 4. Hydrology. In N*ational Engineering Handbook*, US. Department of Agriculture-Soil Conservation Service: Washington, DC.

86 - Monteith, JL, Evaporation and the environment. p. 205-234. *In* The state and movement of water in living organisms. 19th Symposia of the Society for Experimental Biology. 1965. Cambridge Univ. Press, London, UK.

87 - Allen, RG, Jensen, ME, Wright, JL, Burman, RD, Operational estimates of evapotranspiration. Agron. J. 1989. 81, 650-662.

88 - Priestley, CHB., Taylor, RJ, On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather. Rev. ,1972. 100, 81-92.

89 - Hargreaves, GH, Samani, ZA, Reference crop evapotranspiration from temperature. Applied Engineering in Agriculture. 1985, 1, 96-99.

90 - Chow, VT, Maidment, DR, Mays, LW, Applied hydrology. 1988. McGraw-Hill, Inc., New York, NY.

91 - Cunge, JA, On the Subject of a Flood Propagation Computation Method (Muskingum Method). Journal of Hydraulic Research. 1969. 7(2), 205-230.

92 - Arnold, JG, Allen, PM, Bernhardt, G. A comprehensive surface-groundwater flow model. J. Hydrol. 1993. 142:47-69.

93 - Arnold, JG, Allen, PM. Automated methods for estimating baseflow and ground water recharge from streamflow records. J. American Water Resour. Assoc. 1999, 35(2), 411-424.

94 - Sloan, PG., Moore, ID. Modeling subsurface stormflow on steeply sloping forested watersheds. Water Resources Research. 1984. 20(12), 1815-1822.

95 - Band/Uol (Vila MAR). 2011. Cheia do rio Piracicaba causa inundações no interior de SP. Available at: http://noticias.band.uol.com.br/cidades/noticia/?id=100000386680. Acessed on: 2015-02-06.

96 - ANA/DAEE, Agência Nacional de Águas/Departamento de Águas e Energia Elétrica, 2014. Resolução Conjunta ANA/DAEE n◦ 1672, 17 de Novembro de 2014 (Brazilian National Water Agency (ANA)/São Paulo Water and Electrical Energy Department (DAEE) Joint Resolution), Brazil. Available: http://www.daee.sp.gov.br/images/documentos/cantareira/ 1672ANADAEE.pdf. Accessed on: 2014-19-11.

97 - ANA/DAEE, Agência Nacional de Águas/Departamento de Águas e Energia Elétrica. 2015. Boletim diário ANA/DAEE de monitoramento do Sistema Cantareira situação do sistema equivalente - 06/02/2015, Sistema Cantareira. Available at: http://arquivos.ana.gov.br/ saladesituacao/ BoletinsDiarios/DivulgacaoSiteSabesp_6-2-2015.pdf. Accessed on: 2015-02-06.

98 - Globo. 2014. Vazão do Rio Piracicaba fica 96% abaixo da média e bate novo recorde. Manancial registrou volume de 3,46 mil litros de água por segundo. Situação neste sábado (22) foi a pior observada nos últimos 30 anos. Available at: http://g1.globo.com/sp/piracicaba-regiao/noticia/2014/11/vazao-do-rio-piracicaba-fica-96-abaixo-da-media-e-bate-novo-recorde.html. Acessed on: 2015-02-06.

99 - Globo. 2015. Com chuva, Cantareira e maioria dos reservatórios se mantêm estáveis. Available at: http://g1.globo.com/sao-paulo/noticia/2015/02/com-chuva-cantareira-e-maioria-dos-reservatorios-se-mantem-estaveis.html. Acessed on: 2015-02-06.

100 - Climatempo. 2015. Precipitation Predictions and Reservoir Levels of the Cantareira System. Available at: http://www.climatempo.com.br/destaques/tag/sistema-cantareira/. Accessed on: 2015-02-06.

101 - Winchell, M, Srinivasan, R, Di Luzio, M, Arnold, J, *ARCSWAT interface for SWAT2005: User's Guide*. Texas Agricultural Experiment Station and USDA Agricultural Reasearch Service, Temple, Texas. 2007. Available: http://www.geology.wmich.edu/sultan/5350/Labs/ ArcSWAT _Documentation.pdf. Accessed on: 2013-02-10.

102 - NASA and METI– National Aeronautics and Space Administration and Ministry of Economy, Trade, and Industry. 2011. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM data. Available: http://reverb.echo.nasa.gov/reverb/#utf8=%E2%9C%93& spatial_map=satellite&spatial_type=rectangle. Accessed on: 2012-07-13.

103 - Molin, PG, Miranda, FTS, Sampaio, JV, Fransozi AA, Ferraz, SFB, Mapeamento de uso e cobertura do solo da bacia do rio Piracicaba, SP: Anos 1990, 2000 e 2010. Circular Técnica IPEF, 2015 (Instituto de Pesquisas e Estudos Florestais). Available at: http://www.ipef.br/publicacoes/ctecnica/edicoes.asp.

104 - Oliveira, JB, Soils from São Paulo State: description of the soil classes registered on the pedologic map. Campinas: Agronomic Institute, 1999. 112p. (Scientific Committee n.45). (Solos do Estado de São Paulo: descrição das classes registradas no mapa pedológico. Campinas: Instituto Agronômico, 112p. (Boletim Científico n.45)).

105 - Sartori, A, Lombardi Neto, F, Genovez, AM, Classificação Hidrológica de Solos Brasileiros para a Estimativa da Chuva Excedente com o Método do Serviço de Conservação do Solo dos Estados Unidos Parte 1: Classificação. *RBRH* – Revista Brasileira de Recursos Hídricos. 2005. 10 (4): 05-18.

106 - Saxton KE., Rawls WJ. Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. Soil Science Society of Agronomy Journal. 2006. 70(5), 1569-1578. doi: 10.2136/sssaj2005.0117.

107 - ANA - Agência Nacional de Águas. 2012. Hydrologic Data – Precipitation and flow historic records. Brasil. Available: http://hidroweb.ana.gov.br/. Accessed on: 2012-03-10.

108 - DAEE – Departamendo de Águas e Energia Elétrica. 2012. Hydrologic Data – Precipitation and flow historic records. São Paulo, Brasil. Available: http://www.daee.sp.gov.br/. Accessed on: 2012-03-15.

109 - Zhang, X. and Srinivasan, R. GIS-Based Spatial Precipitation Estimation: A Comparison of Geostatistical Approaches. JAWRA- Journal of the American Water Resources Association, 2009. 45: 894–906. doi: 10.1111/j.1752-1688.2009.00335.x.

110 - Thiessen A H. Precipitation for large areas. *Monthly Weather Review*, 1911**.** 39: 1082-1084.

111 - Burrough, PA, McDonnell, RA, Creating continuous surfaces from point data, in: Burrough, PA, Goodchild, MF, McDonnell, RA, Switzer, P, Worboys M. (Eds.), Principles of Geographic Information Systems, 1998. Oxford University Press, Oxford, UK, 333pp.

112 - INMET – Instituto Nacional de Meterologia. Banco de Dados Metológicos para Ensino e Pesquisa (BDMEP). Climate Database for Research and Education. Available on: http://www.inmet.gov.br/portal/index.php?r=bdmep/bdmep. Acessed on: 2013-02-01.

113 - ESALQ/USP – Escola Superior de Agricultura "Luiz de Queiroz"- Universidade de São Paulo. Meteorological Data. Piracicaba, Brasil. Available: http://www.leb.esalq.usp.br/posto/. Accessed on: 2013-02-10.

114 - Allen, RG, Pereira, LS, Raes, D, Smith, M, Crop evapotranspiration (guidelines for computing crop water requirements). FAO Irrigation and Drainage, 1998,Paper No. 56. FAO, Rome, Italy. p. 290.

115 - Linacre, E, Climate and Data Resources: A Reference and Guide. Routledge, 1992. London. 365 p.

116 - Smith, M, CROPWAT, a computer program for irrigation planning and management. FAO Irrigation and Drainage 1992. Paper 46, FAO, Rome.

117 - Ferraz, FFB, Avaliação da relação entre distribuição espacial da precipitação e os componentes do escoamento em bacia tropical de meso escala. Revista GeoUSP, 2003. 13. http://www.geografia.fflch.usp.br/publicacoes/Geousp/Geousp13

118 - Mortatti, J; Probst, JL; Bortoletto Jr, MJ, Piracicaba river basin: mechanical and chemical erosions. São Paulo, UNESP, Geociências, 2003. 22 (1); 75-81.

119 - PCJ & COBRAPE (PCJ/COBRAPE). Plano das Bacias Hidrográficas dos Rios Piracicaba, Capivari e Jundiaí 2010-2020, com Propostas de Atualização do Enquadramento dos Corpos d´água e de Programa para Efetivação do Enquadramento dos Corpos d'água até o ano de 2035. Relatório Final. Piracicaba: COMITÊ PCJ/COBRAPE, 2010. 815p.

120 - PCJ & IRRIGART (PCJ/IRRIGART). Relatório da Situação dos Recursos Hídricos das Bacias Hidrográficas dos Rios Piracicaba, Capivari e Jundiaí – 2002/2003. Relatório Final. Piracicaba: COMITÊ PCJ/IRRIGART, 2004.

121 - Abbaspour KC. SWAT-CUP4: SWAT Calibration and Uncertainty Programs - A User Manual. © Eawag. 2011. Available: http://www.eawag.ch/forschung/siam/software/swat/ index_EN. Accessed on: 2013-05-13.

122 - Abbaspour KC, Johnson CA, van Genuchten, MTh. Estimating Uncertain Flow and Transport Parameters Using a Sequential Uncertainty Fitting Procedure. *Vadose Zone Journal*, 2004. 3:1340–1352.

123 - Kling, H, Fuchs, M, Paulin, M. Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios. Journal of Hydrology, 2012. 424-425 (6), 264-277. doi:10.1016/j.jhydrol.2012.01.011.

124 - Criss RE, Winston WE. Do Nash values have value? Discussion and alternate proposals. Hydrological Processes. 2008, 22: 2723-2725. doi: 10.1002/hyp.7072

125 - Migliaccio KW, Chaubey I. Spatial distributions and stochastic parameter influences on SWAT flow and sediment predictions. Journal of Hydrologic Engineering. 2008. 13(4):258-269.

126 - Quadro MFL, Machado LHR, Calbete S, Batista NNM, Sampaio G; Climatologia e Precipitação e Temperatura no período de 1986 a 1996. Revista Climanálise - Edição Comemorativa de 10 anos - CPTEC/INPE. 1996.

127 - IBGE, cartographer Mapa de Unidades Climáticas. www.ibge.gov.br: Instituto Brasileiro de Geografia e Estatística, IBGE; 1997.

128 - Bressiani, DA, Srinivasan, R, Jones, CA, Mendiondo, EM. Effects of different spatial and temporal weather data resolutions on the streamflow modeling of a semi-arid basin, Northeast Brazil. Int J Agric & Biol Eng, 2015; 8(3): 125−139.

129 – Braga Jr., BPF; Conejo, JGL, Paios, JCF, Balanço Hídrico do Estado de São Paulo, 1991,UNESCO.

130 - Camargo, AP.; Camargo, MBP. Uma revisão analítica da evapotranspiração potencial. *Bragantia*, 2000. Campinas, 59(2), 125-137.

131 - Gouvêa, J RF. Mudanças climáticas e a expectativa de seus impactos na cultura da cana-de-açúcar na região de Piracicaba, SP. Master Thesis, University of São Paulo, Piracicaba, Brazil. 2008.

132 - Lima, WP. A silvicultura e a água : ciência, dogmas, desafios. Rio de Janeiro: Instituto BioAtlântica, 2010, (1) 1: 64. ISBN 978-85-60840-03-8.

133 - Sansigolo, CA,. Estimativas climatológicas de evapotranspiração regional em Piracicaba-SP. Revista Brasileira de Meteorologia, 2002. 17(1), 11- 18.

134 - Sentelhas, PC, Pereira, AR; Marin, FR; Angelocci, LR; Alfonsi, RR.; Caramori, PH.; Swart, S, BHBRASIL - Balanços hídricos climatológicos de 500 localidades brasileiras, 2003. http://www.lce.esalq.usp.br/bhbrasil/Saopaulo/

135 – Mu, Q; Zhao, M; Running, SW. 2011. Improvements to a MODIS Global Terrestrial Evapotranspiration Algorithm. Remote Sensing of Environment. 115, 1781-1800. doi:10.1016/j.rse.2011.02.019.

136 - van Griensven, A, Maskey, Stefanova, A. 2012. The use of satellite images for evaluating a SWAT model: Application on the Vit Basin, Bulgaria. International Congress on Environmental Modelling and Software Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany. http://www.iemss.org/sites/iemss2012// proceedings/I4_0784_Stefanova_et_al.pdf

137 - Mu, Q; Heinsch, FA; Zhao, M; Running, SW. 2007. Development of a global evapotranspiration algorithm based on MODIS and global meteorology data. Remote Sensing of Environment, 111, 519–536.

138 - Velpuri NM; Senay GB; Singh RK; Bohms S; Verdin JP. A comprehensive evaluation of two MODIS evapotranspiration products over the conterminous United States: Using point and gridded FLUXNET and water balance ET. Remote Sensing of Environment, 2013. 139, 35-49. doi.org/10.1016/j.rse.2013.07.013.

139 - Thompson, GD. The production of biomass by sugarcane. Proc. S. Afr. Sugar Technol. Assoc. 1978. 52:180-187.

140 - Arnold, JG, Allen, PM, Muttiah, R, Bernhardt G. Automated base flow separation and recession analysis techniques. Ground Water, 1995. 33(6), 1010-1018.

141 - Coelho, ST. Mecanismos para Implementação da cogeração de eletricidade a partir de biomassa. Um modelo para o Estado de São Paulo. Doctoral Dissertation. University of São Paulo, São Paulo, 1999.

142 - IBGE, Instituto Brasileiro de Geografia e Estatística (Brazilian Institute of Geography and Statistics). Anuário Estatístico do Brasil. Rio de Janeiro, several years.

143- Arnold JG, Allen PM, Muttiah R, Bernhardt G. Automated base flow separation and recession analysis techniques. 1995. *Ground Water* 33(6), 1010-1018.

144- Beven K. A manifesto for the equifinality thesis. Journal of Hydrology. 2006. 320: 18–36.

5. *Searching for better model performance and reduced optimization time: different calibration methods on different watershed locations*

A modified version of this chapter will be shortly submitted to a peer-review international journal, with the following co-authors: Danielle de Almeida Bressiani, Raghavan Srinivasan, Eduardo Mario Mendiondo.

Abstract

Hydrological models involve a large number of calibration parameters to represent the spatial heterogeneity of the watershed and its physical processes. Due to this complexity, manual calibration becomes a less feasible option, since manually it is harder to visualize relationships between model parameters and watershed physical characteristics and requires a trained hydrologist with a good knowledge of the watershed and of the model used. However, when a large number of interactive highly complex parameters, most times with non-linear relationships with model outputs, are adjusted, results can be unpredictable, in order to help on this process there are automatic calibration methodologies, as the model calibrator: SWAT-CUP. This study aims to test different methods for flow calibration, to try to understand how much of an increase on model performance efficiency, and decrease of processing time, can be obtained with different calibration techniques. Therefore two different methods were chosen: a supervised calibration using the Sequential Uncertainty FItting (SUFI-2) and Particle Swam Optimization (PSO). And at the same time this study aims to show how much of a difference in a diverse watershed the interior processes have in the calibration process, therefore, two different daily stremflow calibrations were performed: 1) only for the most downstream gauge station of the watershed; 2) in three different regions with similar physical characteristics (land use, geomorphology and climate). The performance of the model calibration and validation were evaluated using multiple statistical criteria, based on streamflow. The model was calibrated for the Piracicaba watershed, 12,600 km^2, in southeast Brazil, the model performances of each one of the 4 different calibrations were evaluated at 16 gauge stations. The calibration using SUFI2 and manual input for three locations had the best performances. The processing time of SUFI2, compared with PSO, was a lot less. Also the identification of different physical characteristics

for calibration was important to better model the different regions with its physical and spatial characteristics taken into account, and therefore to obtain better results.

Keywords: Calibration, Interior processes, SUFI2, PSO, SWAT-CUP, Piracicaba Watershed.

5-1. Introduction

A complex hydrologic model possesses a multitude of parameters[1]. With the increased development of Geographical Information Systems (GIS), distributed and semi-distributed hydrologic models, the capacity and speed of computers and spatially distributed data availability, the use of complex hydrologic and watershed models has significantly increased to deal with different water resources challenges. With this popularity growth the calibration problem has substantially increased[2].

These complex models have many parameters that cannot be directly measure, because of measurement limitations and errors; scaling and spatial variability factors, therefore they won't be exactly known and a model calibration will be necessary[1,3]. The success of a hydrologic model application is subjected to how well the calibration was performed[4]. But the complex structures and great amount of parameters pose a very challenging problem for calibration[5]. Therefore automatic calibration techniques on high performance computing systems have also become increasingly popular[6].

But, even so, running complex watershed models (as the Soil and Water Assessment Tool - SWAT) still is time consuming and computationally intensive[5]. Hence the time consumed for calibration of large watersheds is massive. Therefore the selection of reliable and efficient methodologies to spend well time and resources is a very important topic of research. Many authors have evaluated the performance of different automatic algorithms [4,7,8,9,10,11,12].

At the same time, much has been discussed and advised in the literature in relation to multi-site calibration[10 13,14 15,16,17]. Multi-site calibration is definitely worthwhile, especially to better represent and accurately model watershed's different interior processes and characteristics[18,19,20]. Nevertheless if automatic calibration or even only running complex models are already time and computing demanding, with the increase of data points to perform multi-site calibration the demands can be exacerbated. Especially if in a large watershed all the available large number of gauge stations are used to perform calibration, rather than selecting some stations looking at the physical dynamics and characteristics of the regions.

Therefore given all these challenges, this paper aims to help users to make this process easier, even though still using a complex model for a complex watershed. It aims to test different flow calibration methods, to try to understand how much of an increase on model performance efficiency, and decrease on processing time, can be obtained. Therefore two readly available and easy to use methods were chosen: a supervised calibration using a local optimization algorithm: the Sequential Uncertainty FItting (SUFI-2) and a global optimization algorithm: Particle Swam Optimization (PSO), both from the SWAT-CUP calibration software. And at the same time this study aims to see how much of impact the interior processes have in the calibration process, therefore, two different daily stremflow calibrations were performed: 1) only for the most downstream gauge station of the watershed; 2) in three different regions with similar physical characteristics (land use, geomorphology and climate).

5-2. Methods

5-2.1. The Watershed Model

The Soil and Water Assessment Tool (SWAT) a watershed-scale ecohydrological model has unfold internationally as a robust tool for water resources science, engineering and management[17,21,22,23]. SWAT is a product of more than 40 years of *United States Department of Agriculture - Agricultural Research Service* (USDA-ARS) modeling experience[24]. It is a physical-process-based complex semi-distributed model that simulates water, sediment, nutrient and pesticide transport, as well as crop growth and management practices at a watershed scale [25,26].

In SWAT the watershed is divided in multiple delineated subbasins based on the Digital Elevation Map (DEM), which are further divided into lumped hydrologic response units (HRUs), that consist of homogeneous soil, landuse, and landscape characteristics and are not spatially identified within the given subbasin[26,27]. Flow and pollutant losses are first estimated at HRU level, then aggregated to subbasin level and finally routed through the simulated stream system to the watershed outlet [17,22,27]. SWAT has been applied in many studies around the world[22] and in well over 100 published studies in Brazilian watersheds[23], with a range of different scopes, mainly related to: water balance, land management, sediment, nutrient and pesticide transport, water quality, climate and land use changes scenarios, and the impacts of best management practices[17,22,26,27].

5-2.2. Calibration Algorithms and Software

Two different calibration methods and algorithms were tested for this study through SWAT-CUP (SWAT Calibration and Uncertainty Procedures) software package[28]. The software is a public domain program for sensitivity analysis, calibration, validation, and uncertainty analysis of SWAT models, and it contains different calibration procedures, as Sequential Uncertainty Fitting (SUFI2)[29,30], Particle Swam Optimization (PSO)[28], Generalized Likelihood Uncertainty Estimation (GLUE)[31], Parameter Solution (ParaSol)[32], and Markov Chain Monte Carlo (MCMC)[33]. The two algorithms tested were SUFI2 and PSO.

There are many publications applying SWAT using SWAT-CUP and SUFI2 for calibration, validation and/or uncertainty analysis[30,34,35,36,37,38,39,40,41]. SUFI2 can provide a semi-automated iterative approach, where the user can perform both manual and automated calibration, adjusting and updating the parameters and its ranges between auto-calibration simulations [17,30] .

SUFI2 maps various input uncertainties indirectly through parameter uncertainties as uniform distributions, while the output uncertainties are estimated by the fit between observed data and the 95% prediction uncertainty band (95PPU), measured through the *P-factor*. The *R-factor* accounts for the thickness of the 95PPU divided by the standard deviation of the observed data. The 95PPU is calculated at the 2,5% and 97,5% levels of the cumulative distribution of the outputs of variables obtained from Latin Hypercube Sampling. The goodness of fit and uncertainty of the calibration are examined at every step by the balance between *P* and *R-factors*[28,30,34,40].

PSO has been applied to solve various optimization problems in a wide range of applications [28,42,43]. Many studies used PSO for calibration and uncertainty analysis of hydrological and watershed modelling, as SWAT[41,44,45,46,47,48]. PSO is a population based stochastic optimization algorithm inspired by social behavior of bird flocking and their ability to change directions and regroup; to adapt in an optimal form by sharing information[42,43,50,51]. In PSO each potential solution (particle) has an assigned randomized velocity. The particles then fly through the design space problem towards its and its neighbors' previous best positions.

PSO is similar to Genetic Algorithms (GA)[52,53]; both initialize with a population of random solutions and are based on information sharing to enhance the search and update generations, searching for the optimal solution. However, unlike GA; PSO has no evolution operators, such as crossover and mutation[28]. Many studies have compared PSO and GA for different optimization applications[51,54,55,56]. Lima Jr. et al.[55] stated that PSO technique performed better than GA in relation to data homogeneity around the mean or median and that PSO is more robust and consistent than GA. Banerjee et al.[54] concluded that PSO has better computational efficiency and stable convergence characteristics than GA. Panda and Padhy[56] observed that, from an evolutionary point of view, the performance of PSO was better than that of GA, arriving at its final parameter values in fewer generations than the GA, although the computational time for PSO was larger. Hassan et al.[51] investigated eight test problems and showed that PSO was more computational efficient than GA to reach the same effectiveness, although as the authors stated further analysis show that different computational efforts are problem dependent.

5-2.3. Piracicaba Watershed SWAT Model set-up

The ~12,600 km² Piracicaba watershed is part of the Paraná River watershed, in southeast Brazil (Figure 5-1) with average yearly precipitation of 1400 mm and average monthly flow of 135 m^3/s (at downstream gauge station 16, Figure 5-1). The Piracicaba watershed is predominately rural, mainly with sugar cane and pasture, but it has considerable areas with forest cover, eucalyptus and citrus plantations, as well as urban areas (in which about 3.5 million people live). The watershed also supplies water for the São Paulo Metropolitan Region.

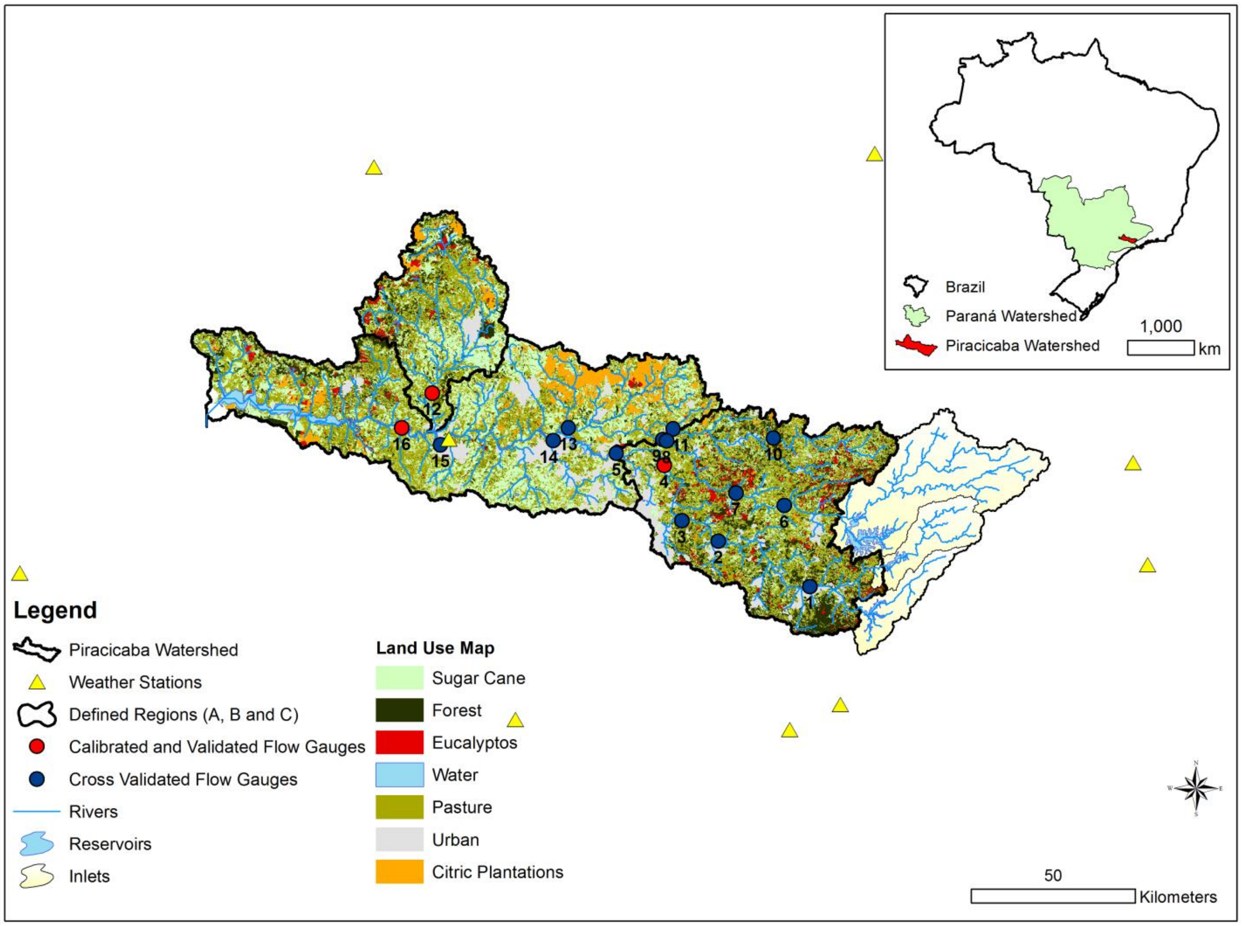

Figure 5-1- Location of Piracicaba Watershed, Land Use and Weather and Streamflow Gauge Stations

The Piracicaba SWAT model setup was done in ArcSWAT 2012 interface[58] on ArcGIS 10.0 (service pack 5)[59]. It required topographic, soil, land use, climate, agriculture management data, as well as streamflow and available data for calibration and validation. The model was constructed using freely available information from the web, or provided by government and water management agencies, Figure 5-1 lists their description, resolutions and sources.

The modeled area of the Piracicaba watershed is of 10,454 Km^2, which was further divided in ArcSWAT into 523 subbasins, with an average area of 20 Km^2. The upstream areas of the watershed, upstream of the Cantareira System reservoirs, were not modeled on the SWAT project; instead the reservoirs discharges were considered as inlets to the model. Since there was missing data for the flow records used for the inlets, data regressions between downstream gauge stations were done to complete the time series, if the missing data had less than ten consecutive days, if more than ten days of flow data was missing a long-term monthly average for the period was used. Based on previous calibration study conducted on Chapter 4] the evapotranspiration method chosen was Priestley Taylor, and the daily curve number calculation method was based on Plant ET, and ALPHA_BFs (base flow recession constant) initial values were based on the Baseflow Filter program[60,61], the averages of the gauge stations of each of the three regions was used.

5-2.4. Calibration Sites and Procedure

The watershed's interior processes effect the watershed simulation and calibration, and it has being greatly discussed in the literature that they should be incorporated on the calibration process, to better represent the reality (with multi-site calibration, etc). This study performs and compares two different site calibrations to understand these effects for the case study, and how important they may be or not, as also using two different calibration algorithms. The Piracicaba Watershed was calibrated 1) in three defined different regions with similar physical characteristics within (land use, geomorphology and climate) and 2) only for the most downstream gauge station of the watershed. The subdivision was based on the land uses, soil types, aquifers, slopes, drainage density, eco-regions and natural vegetation, and climate. Chapter 4 better discuss this sub-division and also the calibration using SUFI-2 for these defined regions. The sub-divisions (A, B and C) and the gauge stations used for calibration are presented in Figure 5-1.

Table 5-1 - Data Description and Sources for the Piracicaba SWAT Model

Data Type	Description	Resolution	Source
Digital Elevation Map (DEM)		1 arc-second, approximately 30 m resolution	Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) [62]
Soils map		1:500,000	Oliveira[63] digitalized by Piracicaba-Capivari-Jundiai Water Committee
Soils characteristics	Soil depths, texture, and organic matter Hydrological group Other soil parameters were estimated based on Pedo-transfer functions	Typical soil profile per soil type from São Paulo State	Oliveira [63] Sartori *et al*.[64] Saxton and Rawls[65]
Land use map	developed from Landsat 5 TM 2010	30 m-pixel resolution: 1:50,000	Molin *et al*.[66]
Agriculture and Forest Management and Parameters	Sugarcane Atlantic Forest, Eucalyptus and Citrus plantations	Planting, Harvesting, Fertilization Initial, minimum and maximum leaf area index, initial biomass and total number of heat units needed for growth	Local Farmers Specialist from Paper Industry, SWAT team
Precipitation	Precipitation records were interpolated[a] from 189 stations with data for different time periods	Daily (mm)	Brazilian National Water Agency[67] and São Paulo State Water and Electrical Energy Department [68]
Flow	River Discharges	Daily Mean (m^3s^{-1})	Brazilian National Water Agency[67] and São Paulo State Water and Electrical Energy Department[68]
Climate	Daily maximum and minimum temperatures, wind speed, humidity and insolation (converted to solar radiation[b])	Daily Mean	National Meteorological Institute [69] and from one station at the University of São Paulo [70]

[a]Precipitation records from the gauge stations were interpolated in ArcGIS using PCP_SWAT plug-in[49] and Inverse Distance Weighted (IDW) [71] (which presented better geostatistical results than Thiessen Polygons [72]) to establish a model with one interpolated precipitation data series per subbasin;
[b]Insolation was converted to solar radiation[73,74,75].

First a global sensitivity analysis was performed, using SUFI-2 for each of the three gauge stations; the most sensitive parameters for each location were selected. Then the four calibrations were conducted: 1) using SUFI-2 with manual input for the three regions, starting with Region A, then B and C (Gauge stations 4, 12 and 16 respectively); 2) SUFI-2 only for the downstream gauge station 16; 3) PSO for the three regions, starting with regions A and B, and then C (Gauge stations 4, 12 and 16 respectively); and 4) PSO only for the downstream gauge 16. The calibration was performed for a twelve years period (2000-2011) (except on gauge station 4, which does not have data for the first 2 years). A cross validation to evaluate the calibrations' performances within the watershed was conducted by comparing the data available on the other gauge stations (Figure 5-1). The validation period was established from 1980 to 1999 (20 years).

The objective functions used for calibration were Nash-Sutcliffe (NSE)[76] and the coefficient of determination multiplied by the line regression coefficient bR^2 [77]. But different evaluation metrics were calculated to analyze distinct aspects of the correspondence of the simulated flows with the observed ones, as the coefficient of correlation R^2, percent bias (PBias)[78], mean square error (MSE) and RMSE-observations standard deviation ratio (RSR)[79]. Three of these statistics (NSE, PBias and RSR) were also evaluated based on model evaluation performance ratings proposed by Moriasi et al.[80].

5-3. Results and Discussion

The first calibration (1) with SUFI-2 in the three locations was performed using manual input and several different iterations; a total of ~500 runs were conducted for calibrating the three gauge stations of regions A, B and C. This procedure was explained in detail on Chapter 4. The second calibration (2) only on the most downstream gauge station (16, Figure 5-1 was done after 2 iterations and a total of 230 runs. The third calibration (3) was performed using PSO, first for the regions A and B, and after those were calibrated, for region C, a total of 4500 runs were done to calibrate these regions and watershed. Then at last, the fourth calibration (4) performed using PSO only for gauge station 16, was done with 750 runs in SWAT-CUP. The run times for calibration are proportional to the number of runs. The SUFI-2 method took overall less runs and time, as other authors have stated[11,12].

Although SUFI-2 method was used a combined approach with manual input was done, therefore there was time spent in between the iteration to the next one. And for the calibration (1) with SUFI-2 for the three locations, since the Sub-regions A, B and C were calibrated separately, smaller projects were created and run time was much faster. The computational time for all the runs for the SUFI2 was smaller than 4 days. The PSO runs took from 8 (for the 750 runs) days to 45 (4500) days for this project, using the same computer power. In Table 5-3 the calibrated parameters, initial values and final calibrated values for each performed calibration are shown.

Table 5-2 brings few statistics (NSE, Br^2 and PBias) for the four calibrations performed for the three reference gauge stations of the three sub-regions defined. Overall for all calibrations the results are very good, even for gauge-stations 4 and 12 that were not calibrated on the calibrations (2) and (4).

Table 5-2 -– Performance Metrics for the four calibrations on the selected gauge stations

			(1) SUFI2 on 3 locations			(2)SUFI2 only downstream			(3) PSO on 3 locations			(4) PSO only downstream		
Gauge Station	Drainage Area (km2)	Sub-region	NSE	Br^2	PBias	NSE	Br^2	PBias	NSE	Br^2	PBias	NSE	Br^2	PBias
4	2308	A	0.76	0.86	3.95	0.75	0.81	-7.98	0.71	0.79	22.98	0.71	0.76	-1.29
12	1581	B	0.66	0.72	-4.36	0.61	0.68	-13.61	0.64	0.75	7.88	0.61	0.69	-1.74
16	11040	C	0.83	0.89	8.29	0.83	0.91	2.46	0.78	0.85	22.64	0.78	0.87	11.45

Table 5-3 - Calibrated Parameters

Parameters and file	Parameters' Description	Default SWAT	Initial Ranges		Calibrated Parameters							
					1 (SUFI2, 3 Regions)			2 (SUFI2, outlet only)	3 (PSO, 3 Regions)			4 (PSO, outlet only)
			Min	Max	A	B	C	Entire Watershed	A	B	C	Entire Watershed
ESCO.hru	Soil evaporation compensation factor	0.95	0.65	0.85	0.75			0.75	0.72	0.77	0.72	0.76
CNCOEF.bsn	Plant ET curve number coefficient	1	0.5	0.75	0.5			0.50	0.75			0.75
SURLAG.bsn	Surface runoff lag time (days)	4	0.05	12	0.086			0.07	0.10			0.06
SLSUBBSN.hru	Average slope length (m)	--	-0.05%	0.05%	-4.15%			-0.04	0.06	0.02	0.05	-0.05
GW_DELAY .gw	Groundwater delay time (days)	31	-20	70	95	95	93.23	65.30	52.49	48.80	49.02	85.06
GW_REVAP.gw	Groundwater "revap" coefficient	0.02	0.02	0.1	0.02*	0.03	0.07	0.08	0.05	0.05	0.03	0.08
REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	1	3500	4000	3500	3500	3425	3955	3778	3621	3652	3546
RCHRG_DP.gw	Deep aquifer percolation fraction	0.05	0	0.1	0.05*	0.08	0.1	0.09	0.09	0.10	0.07	0.03
GWQMN.gw	Threshold depth of water in the shallow aquifer for return flow to occur (mm)	0	3000	4000	3000	3883	3123	3370	3972	3228	3823	3174
LAT_TTIME.hru	Lateral flow travel time (days)	0	0	15	15	0.4	2.33	0	0	13.55	1.37	2.21
CANMX.hru*	Maximum canopy storage (mm)	0	0	15	15	15	0	0	11.83	12.93	2.21	1.79
CN2.mgt	SCS curve number (moisture condition II)	--	-0.05%	0.05%	-4.50%	-3.62%	4.00%	-0.05	-0.03	-0.03	0.01	-0.01
OV_N.hru	Manning's "n" value for overland flow	--	-0.10%	0.10%	*	-7.67%	*	*	*	*	*	*
r__ALPHA_BF.gw	Baseflow alpha factor (days)	0.03, 0.04, 0.06	-0.05%	0.05%	0.03	0.06	0.05	0.03, 0.04, 0.06*	0.03	0.04	0.03	0.03, 0.04, 0.06*

* Parameters kept as SWAT's default; ALPHA_BF initial values were based on the Baseflow Filter program [60,61] for the three regions.

In Figures 5.2 to 5.6 we present the performance metrics (NSE, Br^2, PBias, MSE, and RSR) for all the 16 gauge stations with data. In Figure 5.2 one can also see a line of NSE=0.5, which was considered a mark for satisfactory performance[80], below this line there are only results from the calibrations (2) and (4), both performed only in the most downstream gauge station.

The results are relative to four gauge stations upperstream of the watershed, the results for these stations were considerably worse for the calibration done with PSO (4), but neither (2) nor (4) are satisfactory, showing the need for a calibration on a more upstream region of the watershed to take into consideration the different dynamics of these areas that were not encompassed in the calibrations done only for the downstream gauge of the watershed. Looking at NSE values greater than 0.7, for example, one can see that the (1) and (2) have more values with higher NSE, (1) has 13 gauge stations (with NSE>0.7) of the 16, (2) has 11, (3) 9 and (4) 7. Also showing that based on the NSE values the overall performance of SUFI2 was better than PSO.

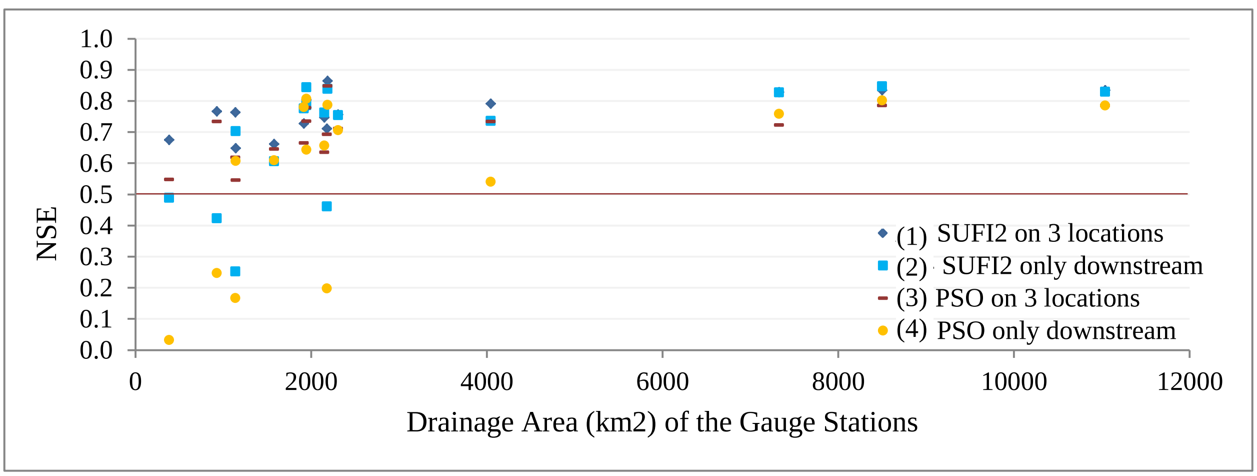

Figure 5-2 — Nash-Sutcliffe (NSE) for all gauge stations and four calibrations performed

In relation to Br^2 the behavior is similar (Figure 5-3), with two of the upperstream gauge stations (with both of the smallest drainage areas) have smaller results for both calibrations only performed in the most downstream gauge of the watershed (done with SUFI2: (2), and PSO: (4)). But overall the results look good, for example Br^2 values greater than 0.8 were found for 11 of the 16 gauge stations for the calibration (1), 10 for (2), 8 for (3), and 6 for (4). Althoght overall the results were good, here also the SUFI2 simulations seemed to have better performance over the PSO ones, as the calibrations performed on three locations better results than the ones performed only on the most downstream gauge.

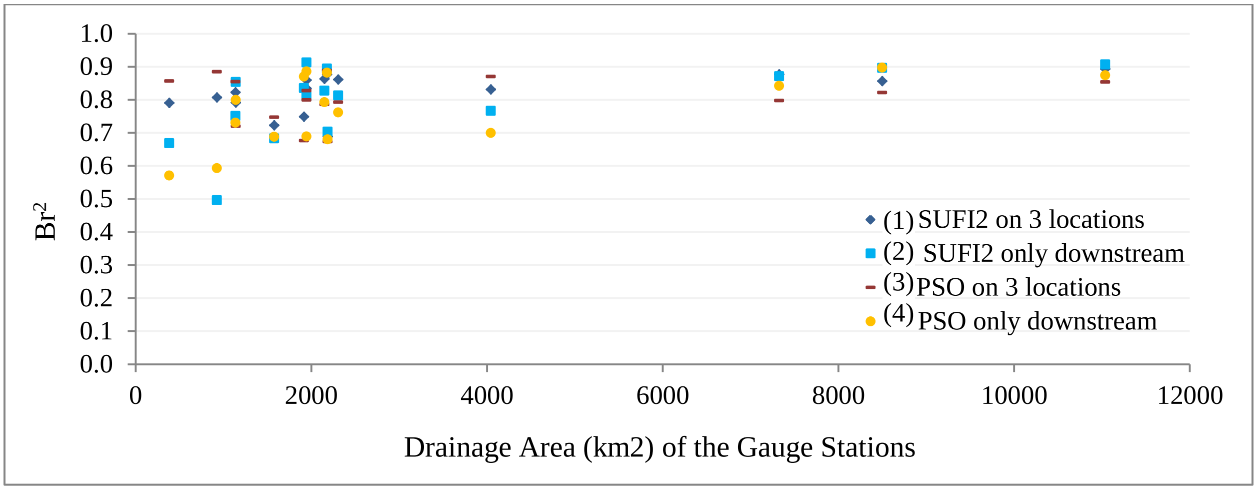

Figure 5-3 - Br^2 for all gauge stations and four calibrations performed

On Figure 5-4 the results for PBias are shown for all the gauge stations on the watershed and for the four calibration methods performed. Looking at the results they are overall very good, most of the values of PBias are in between the -15 to +15 range. Simulations in this range were ranked as good and very good[80]. Although as one can see the PBias values for the simulation with the calibration (3) (PSO on 3 locations) has significant worse results, with an average tendency of over predicting the observed data: with 6 of the 16 gauge stations (40%) being greater than 25 (which is the limit from Moriasi et al[80] to consider it as satisfactory, being then considered unsatisfactory), while calibration A had none result out of this range; and calibration (2) and (4) only for one gauge station each the results of PBias are higher than 25, what was expected since they were calibrated only for the most downstream gauge and therefore could have missed the tendencies of the observed data.

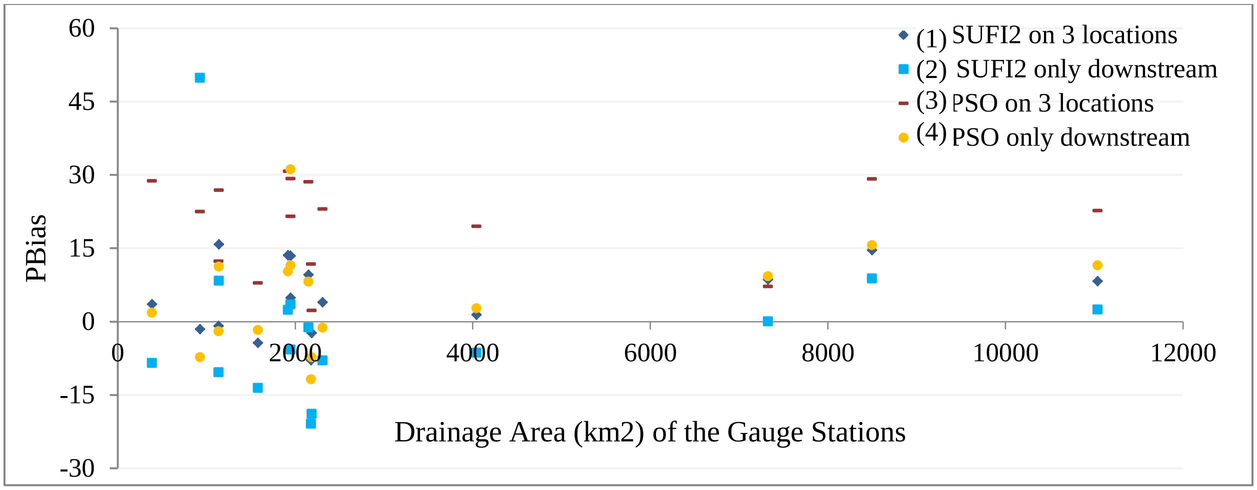

Figure 5-4 - PBias for all gauge stations and four calibrations performed

Figure 5-5 brings the MSE results for all the calibrations done and for all the gauge stations on the watershed. One can see that the greater the drainage area, greater the flow values and therefore the associated squared errors. For the gauge stations with smaller drainage areas the MSE values look similar, while for the three or four downstream gauge stations both PSO calibrations ((3) and (4)) had larger MSE values.

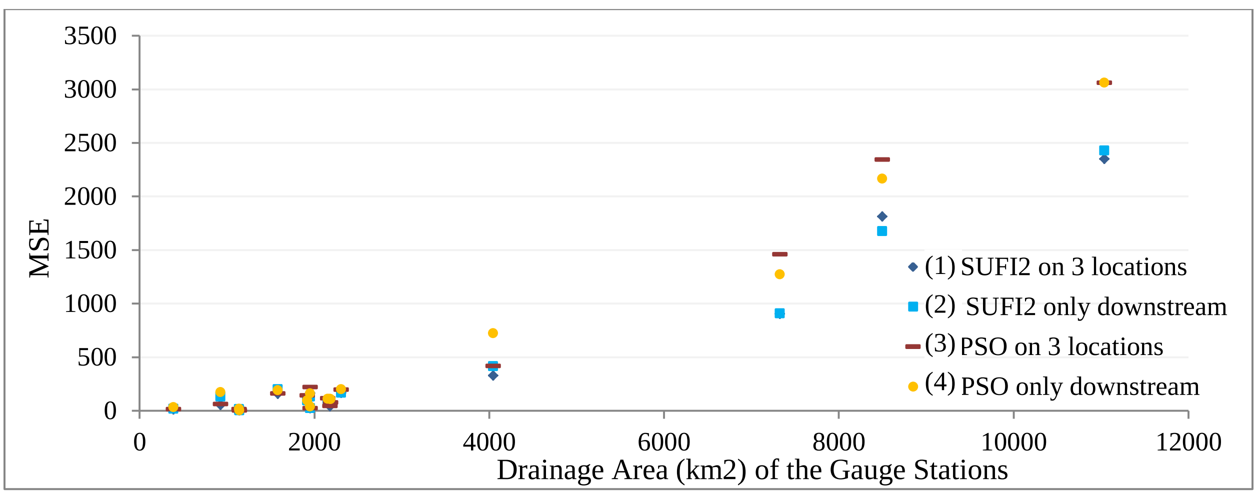

Figure 5-5 - MSE for all gauge stations and four calibrations performed

In Figure 5-6 the RSR results are presented, this performance metric is similar to the MSE, for being also an error index statistic; it is a standardized version of RMSE using the observations standard deviation. In this case, we can see the worst (higher) RSR values for the calibration (4) (PSO only downstream), followed by calibration (2) (SUFI2 only downstream), both with RSR values larger than 0.5 for three gauge stations (with smaller drainage areas), for the rest of the gauges and calibrations the RSR results can be considered very good.

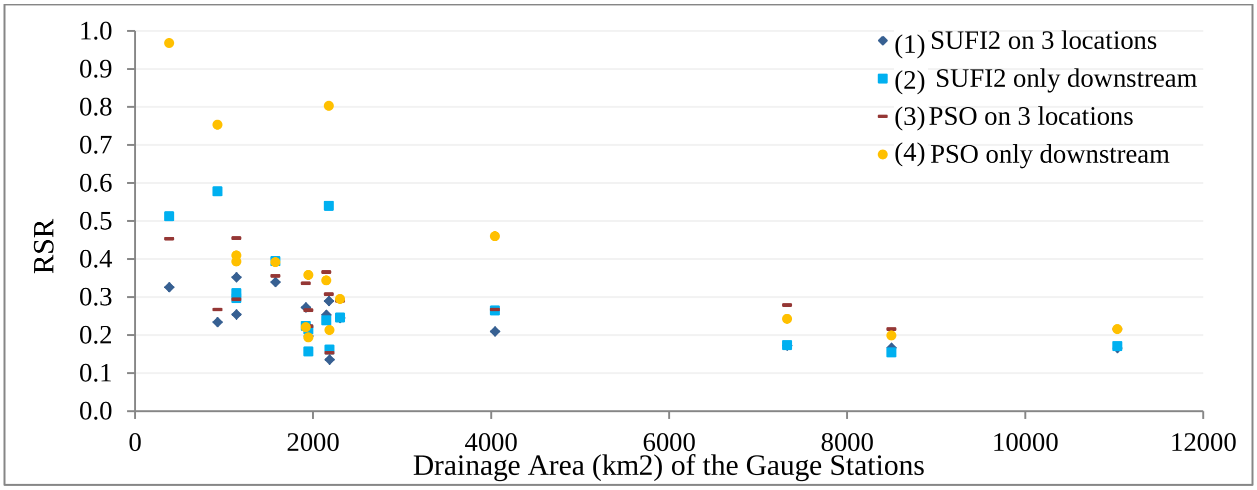

Figure 5-6 - RSR for all gauge stations and four calibrations performed

We classified the results for the four calibrations on the sixteen gauge stations under the performance metrics criteria defined by Moriasi et al. [80], based on NSE, PBias and RSR. Table 5.4 brings these results, under each category, performance metric and calibration performed there is the number of gauge stations from the 16 available that meet the criteria. The best one is the one with calibration (1) (SUFI2 in three locations), with no results in the unsatisfactory category; almost all the results in the good or very good categories (with the exception of 2 out of 48); and with the most in the very good category.

The calibration (2) (SUFI2 only downstream) was the second best in terms of number of very good results, but it has 4 gauge stations that were ranked as unsatisfactory in terms of NSE and one in terms of PBias. Calibration (3) has just as calibration (1) all of the RSR results within the very good criteria, which suggests low error, but has six (the highest of the four calibrations) of the PBias results under the unsatisfactory category, therefore not conserving well the tendency of the observed data. Since the objective function of the calibration was NSE, a balance between these two performance metrics (NSE and PBias) could be advised here.

Calibration (4) (PSO only downstream) has the most total statistics in the unsatisfactory criteria, with eight, four in relation to NSE, one for PBias and three for RSR. These unsatisfactory results for calibrations (2) and (4), as we could see from Figure 5-2 to Figure 5-6 were related to upperstream gauge stations that had the dynamics not well captured on the calibrations performed only downstream, and therefore these regions should be calibrated for better response.

Table 5-4 - Number of Gauge Stations (from the 16 available) for the Calibration Period classified by performance metrics into the categories established by Moriasi et al. [80].

	(1)- SUFI2 on 3 locations			(2) - SUFI2 only downstream			(3) - PSO on 3 locations			(4) - PSO only downstream		
	NSE	PBias	RSR	NSE	PBias	RSR	NSE	PBias	RSR	NSE	PBias	RSR
Very good	**10**	**12**	**16**	**9**	**11**	**13**	**4**	**3**	**16**	**6**	**9**	**13**
Good	5	3	-	2	2	3	7	2	-	2	5	-
Satisfactory	**1**	**1**	**-**	**1**	**2**	**-**	**5**	**5**	**-**	**4**	**1**	**-**
Unsatisfactory	-	-	-	4	1	-	-	6	-	4	1	3

Validation and cross-validation was also performed for 1980-1999 (20 years) for the three calibrated gauge stations (4, 12 and 16), and for the other six gauge stations that had data for this period (gauge stations 2, 5, 6, 8, 10 and 11 - Figure 5-1). We also classified the results for the validation period on the nine gauge stations and for the four calibrations under the performance metrics criteria defined by Moriasi et al. [80], based on NSE, PBias and RSR (Table 5-5).

Table 5-5 - Number of Gauge Stations (from the 9 available) for the Validation Period classified by performance metrics into the categories established by Moriasi et al. (2007).

	(1)- SUFI2 on 3 locations			(2) - SUFI2 only downstream			(3) - PSO on 3 locations			(4) - PSO only downstream		
	NSE	PBias	RSR	NSE	PBias	RSR	NSE	PBias	RSR	NSE	PBias	RSR
Very good	**3**	**8**	**9**	**-**	**1**	**4**	**2**	**7**	**9**	**1**	**9**	**7**
Good	5	1	-	2	-	2	5	2	-	4	-	1
Satisfactory	**1**	**-**	**-**	**2**	**1**	**3**	**2**	**-**	**-**	**2**	**-**	**-**
Unsatisfactory	-	-	-	5	7	-	-	-	-	2	-	1

As in for the calibration period, the best one is the simulation with parameters from calibration (1) (SUFI2 in three locations), with almost all of the results on the very good or good categories, having the only one satisfactory value for NSE which was 0.65. Particularly very good results were found for the sub-region A, especially A1. The validation period evaluated for these nine gauge stations for the calibration (2) (SUFI2 only downstream) yielded bad results, with several on the unsatisfactory category (5 based on NSE values and 7 based on PBias).

The validation with the calibrated parameters from (3) (PSO on 3 locations) also had good results, with most of the statistics in the very good and good categories, both of the NSE values within the satisfactory category were very close to the upper bound of the range for this classification (0.65), therefore the results overall were considered very good for the validation period. The results for the validation (4) (PSO only downstream) are worse than (1) and (3), but they are still good for most of the regions, with unsatisfactory results only for the two gauge stations (10 and 11) on the sub-region A3.

5-4. Conclusions

The best calibration and validation overall for the gauge stations where results were compared was the calibration (1), using SUFI-2 with manual input for the three regions. Almost all results were in the very good and good categories for all gauges and both periods, therefore with a good 30 year simulation. Calibration (2), also done with SUFI-2 but only for the most downstream gauge station, yielded decent results for the calibration period, although it had four gauge stations in the upperstream of the watershed that were ranked as unsatisfactory (the 4 in relation to NSE, and one also in terms of PBias). But this calibration (2) had the worst results for the validation period, with several on the unsatisfactory category (5 based on NSE values and 7 based on PBias).

Calibration (3) using PSO for the three regions also had very good and good results for most gauge stations for the calibration period, but it had six of the PBias results under the unsatisfactory category. But for the validation period the results were good, having all statistics as very good, good and only two as satisfactory. Calibration (4), using PSO only for the most downstream gauge, had bad results for the calibration period especially for the upperstream gauge stations. However for the validation period the results are mostly good, with unsatisfactory results only for the two gauge stations also for one upper portion of the watershed.

SUFI2 for three locations (Calibration (1)) had the best performances. The processing time of SUFI2, compared with PSO, was a lot less, taking a lot less runs to reach better results. But this calibration was more oriented, with input of the hydrologist. Also the identification of different physical characteristics for calibration was important to better model the different regions with its physical and spatial characteristics taken into account, and therefore to obtain better results. In the SUFI2 and PSO calibrations done only downstream this was not able to be taken into consideration, since the processes of the entire watershed were being analyzed. And for the PSO calibrations there was no interaction between iterations. The calibrations on the three different regions showed very consistent and good results overall for the 30 years of simulation, showing the importance of taking in consideration the different processes and characteristics of different regions within the watershed.

5-5. Acknowledgements

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5-6. References

1 - Eckhardt K, Arnold JC, Automatic calibration of a distributed catchment model, Journal of Hydrology, 2001, 251(1-2), 103-109.

2 - Gupta, HV, Sorooshian, S, Yapo, PO, Toward improved calibration of hydrologic models: multiple and non-commensurable measures of information. Water Resour. Res. 1998. 34(4), 751-763.

3 - Beven K, On the future of distributed modelling in hydrology,Hydrological Processes, 2000, 14, (16-17), 3183–3184.

4 - Duan Q, Sorooshian S and Gupta, VK Effective and efficient global optimization for conceptual rainfall-runoff models. Water Resources Research, 1992, 28(4): 1015-1031.

5 - Zhang X, Srinivasan R, Liew MV, On the use of multi-algorithm, genetically adaptive multi-objetives method for multi-site calibration of the SWAT model. Hydrological Process, 2009, doi: 10.1002/hyp.7528.

6 - Vrugt JA, Gupta HV, Bouten W, Sorooshian S. A shuffled complex evolution metropolis algorithm for optimization and uncertainty assessment of hydrologic model parameters. Water Resources Research, 2003, 39(8), 102, doi: 10.1029/2002WR001642.

7 - Cooper VA, Nguyen VTV, Nicell JA. Evaluation of global optimization methods for conceptual rainfall-runoff model calibration. Water Science Technology, 1997, 35(5), 53 – 60.

8 - Kuczera G, Efficient subspace probabilistic parameter optimization for catchment models, Water Resources Research, 1997, 33(1), 177–185, doi: 10.1029/96WR02671

9 - Madsen, H, Wilson, G, and Ammentorp, HC, Comparison of different automated strategies for calibration of rainfall-runoff models, J. Hydrol., 2002, 261, 48 – 59.

10 - Zhang X, Srinivasan R, Zhao K, Liew MV, Evalution of global optimization algorithms for parameter calibration of a computationally intensive hydrologic model, Hydrological Process, 2008, doi: 10.1002/hyp.7152

11 - Yang, J, Reichert, P, Abbaspour, KC, Xia, J, Yang, H. Comparing uncertainty analysis techniques for a SWAT application to the Chaohe Basin in China. Journal of Hydrology, 2008. 358, 1-23. doi: 10.1016/j.jhydrol.2008.05.012

12 - Bilondi MP, Abbaspour KC, Ghahraman B, Application of three different calibration-uncertainty analysis methods in a semi-distributed rainfall-runoff model application, Middle-East Journal of Scientific Research, 2013, 15(9),1255-1263.

13 - Meixner, T, Bastidas, LA, Gupta, HV, Bales, RC. Multicriteria parameter estimation for models of stream chemical composition. Water Resour Res. 2002. 38(3), 9-1-9-9. 10.1029/2000WR000112.

14 - White, KL; Chaubey, I. Sensitivity Analysis, Calibration, and Validations for a Multisite and Multivariable SWAT Model. Journal of the American Water Resources Association *(JAWRA)*. 2005. 41(5),1077-1089.

15 - Ahmadi, M, Ascough II, JC, DeJonge, KC, Arabi, M. Multisite-multivariable sensitivity analysis of distributed watershed models: Enhancing the perceptions from computationally frugal methods. Ecological Modelling. 2014, 279, 54-67.

16 - Yen, H, Bailey, RT, Arabi, M, Ahmadi, M, White, MJ, Arnold, JG. The Role of Interior Watershed Processes in Improving Parameter Estimation and Performance of Watershed Models. Journal of Environmental Quality, 2014. 43,1601–1613. doi:10.2134/jeq2013.03.0110

17 - Arnold JG, Srinivasan R, Muttiah RS, Williams JR. Large area hydrologic modeling and assessment part I: Model development. Journal of the American Water Resources Association, 1998, 34(1): 73‐89. doi: 10.1111/j.1752-1688.1998.tb05961.x.

18 - Yen H, Bailey RT, Arabi M, Ahmadi M, White MJ, Arnold JG.. The role of interior watershed processes in improving parameter estimation and performance of watershed models. Journal of Environmental Quality, 2014, 43: 1601. DOI: 10.2134/jeq2013.03.0110

19 - Yen H, Wang X, Fontane DG, Harmel RD, Arabi M. A framework for propagation of uncertainty contributed by parameterization, input data, model structure, and calibration/validation data in watershed modeling. Environmental Modelling and Software, 2014 54: 211–221. DOI: 10.1016/j.envsoft.2014.01.004

20 - Daggupati P, Yen H, White MJ, Srinivasan R, Arnold JG, Keitzer CS, Sowa SP, Impact of model development, calibration and validation decisions on hydrological simulations in West Lake Erie Basin, Hydrological Processes, 2015, doi: 10.1002/hyp.10536

21 - Arnold JG, Fohrer N. SWAT2000: current capabilities and research opportunities in applied watershed modeling. Hydrological Processes. 2005. 19(3): 563-572. DOI: 10.1002/hyp.5611.

22 - Gassman PW, Reyes MR, Green CH, Arnold JG. The Soil and Water Assessment Tool: Historical development, applications, and future research directions. Transactions of the ASABE, 2007. 50(4): 1211–1250. Available: http://www.card. iastate.edu/environment/items/asabe_swat.pdf. Accessed on: 2013-02-15.

23 - Bressiani, DA, Gassman, PW, Fernandes, JG, Garbossa, LHP, Srinivasan, R, Mendiondo, EM Bonumá, N B, A review of SWAT (Soil and Water Assessment Tool) applications in Brazil: challenges and prospects. Int J Agric & Biol Eng, 2015; 8(3): 9一35.

24 - Williams JR, Arnold JG, Kiniry JR, Gassman PW, Green CH. History of model development at Temple, Texas. Hydrological Sciences Journal. 2008. 53(5): 948-960. DOI: 10.1623/hysj.53.5.948.

25 - Arnold JG, Moriasi DN, Gassman PW, Abbaspour KC, White MJ, Srinivasan R, et al. SWAT: model use, calibration, and validation. Trans. ASABE, 2012. 55(4): 1491-1508. DOI: 10.13031/2013.42256.

26 - Douglas-Mankin KR, Srinivasan R, Arnold JG. Soil and Water Assessment Tool (SWAT) model: Current Developments and Applications. Transactions of the ASABE, 2010. 53(5): 1423-1431. Available: http://swat.tamu.edu/media/87820/douglas-mankin-et-al-2010-trans-asabe-article.pdf. Accessed on: 2014-09-06.

27 - Gassman PW, Sadeghi AM, Srinivasan R. Applications of the SWAT Model Special Section: Overview and Insights. Journal of Environmental Quality ,2014. 43; 1–8. DOI: 10.2134/jeq2013.11.0466

28 - Abbaspour KC. SWAT-CUP4: SWAT Calibration and Uncertainty Programs - A User Manual. © Eawag. 2011. Available: http://www.eawag.ch/forschung/siam/ software/swat/index_EN. Accessed on: 2013-05-13.

29 - Abbaspour KC, Johnson CA, van Genuchten MTh. Estimating Uncertain Flow and Transport Parameters Using a Sequential Uncertainty Fitting Procedure. Vadose Zone Journal, 2004, 3:1340–1352.

30 - Abbaspour KC, Yang J, Maximov I, Siber R, Bogner K, Mieleitner J, Zobrist J, Srinivasan R. Modelling hydrology and water qualit in the pre-alpine/alpine Thur watershed using SWAT. Journal of Hydrology 2007. 333: 413-430.

31 - Beven and Binley, 1992

32 - Van Griensven A, Meixner T. 2006. Methods to quantify and identify the sources of uncertainty for river basin water quality models. Water Science and Technology 53(1): 51-59.

33 - Kuczera G, Parent E. Monte Carlo assessment of parameter uncertainty in conceptual catchment models: The Metropolis algorithm, J. Hydrol., 1998. 211, 69–85.

34 - Abbaspour KC, Rouholahnejad E, Vaghefi S, Srinivasan R, Yang H, Kløve B. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. Journal of Hydrology 2015. 524:733-752. DOI:10.1016/j.jhydrol.2015.03.027

35 - Akhavan S, Abedi-Koupai J, Mousavi SF, Afyuni M, Eslamian SS, Abbaspour KC. Application of SWAT model to investigate nitrate leaching in Hamadan-Bahar watershed, Iran. J. Agric. Ecosystem and Environ 2010. 139(4), 675-688.

36 - Andersson J C M, Zehnder A J B, Jewitt G P W, Yang H. 2009. Water availability, demand, and reliability of in situ water harvesting in smallholder rainfed agriculture in the Thukela River basin, South Africa. Hydrol. Earth System Sci 13(12), 2329-2347.

37 – Bressiani DA, Srinivasan R, Sauvage S, Sanchez Perez JM, Mendiondo EM. Systematic Procedure for Calibrating Complex Watersheds: Case Study Application in Southeast Brazil. Agricultural Water Management, 2016. "In review" (Chapter 4).

38 - Faramarzi M, Abbaspour KC, Schulin R, Yang H. Modeling blue and green water availability in Iran. Hydrol. Proc. 2009. 23(3), 486-501.

39 - Rodrigues DBB, Gupta HV, Mendiondo EM. A blue/green water-based accounting framework for assessment of water security. Water Resour. Res. 2014. 50: 7187–7205. DOI:10.1002/2013WR014274

40 - Schuol J, Abbaspour KC, Srinivasan R, Yang H. Estimation of freshwater availability in the west African subcontinent using the SWAT hydrologic model. J. Hydrol. 2008, 352(1-2), 30-49.

41 - Zhang J, Li Q, Guo B, Gong H. The comparative study of multi-site uncertainty evaluation method based on SWAT model. Hydrological Processes, 2014.1099-1085. DOI: 10.1002/hyp.10380.

42 - Kennedy J, Eberhart R. Particle Swarm Optimization. Proceedings of the IEEE International Conference on Neural Networks: 1995, Perth, Australia; 1942-1945.

43 - Eberhart RC, Kennedy J. A new optimizer using particle swarm theory. Proceedings of the Sixth International Symposium on Micromachine and Human Science: 1995. Nagoya, Japan; 39- 43.

44 - Bilondi MP, Abbaspour KC, Ghahraman B. Application of Three Different Calibration-Uncertainty Analysis Methods in a Semi-Distributed Rainfall-Runoff Model Application. Middle-East Journal of Scientific Research, 2013. 15 (9): 1255-1263. DOI: 10.5829/idosi.mejsr.2013.15.9.11470

45 - Musau J, Sang J, Gathenya J, Luedeling E, Home P. SWAT model parameter calibration and uncertainty analysis using the HydroPSO R package in Nzoia Basin, Kenya. Journal of Sustainable Research in Engineering, 2014. 1 (3): 17-29.

46 - Noor H, Vafakhah M, Taheriyoun M, Moghadasi M.. Hydrology modelling in Taleghan mountainous watershed using SWAT. Journal of Water and Land Development, 2014, 20: 11–18.

47 - Samadi S, Meadows ME. Examining the Robustness of the SWAT Distributed Model Using PSO and GLUE Uncertainty Frameworks. Proceedings of the 2014 South Carolina Water Resources Conference, 2014. Columbia, USA; 1-4.

48 - Zambrano-Bigiarini M, Rojas R. hydroPSO: A Versatile Particle Swarm Optimisation R Package for Calibration of Environmental Models. In EGU General Assembly 2012; 14, EGU2012-10950-2.

49 - Zhang, X, Srinivasan R. GIS-Based Spatial Precipitation Estimation: A Comparison of Geostatistical Approaches. Journal of the American Water Resources Association (JAWRA), 2009, 45(4):894-906. doi:10.1111/j.1752-1688.2009.00335.x

50 - Kennedy J, Eberhart R. Swarm Intelligence. Academic Press: 2001. 1st ed., San Diego, CA.

51 - Hassan R, Cohanim B, de Weck, O, Venter G. A comparison of particle swarm optimization and the genetic algorithm. Proceedings of the 1st AIAA Multidisciplinary Design Optimization Specialist Conference: 2005. Austin, TX; 1-13.

52 - Goldberg D. Genetic Algorithms in Search, Optimization and Machine Learning. Addison-Wesley: Reading, MA; 1989. 1-25.

53 - Davis L. Handbook of Genetic Algorithms. Van Nostrand Reinhold: New York, NY, 1991.

54 - Banerjee T, Chowdhuri S, Sarkar G, Bera J. Performance Comparison between GA and PSO for Optimization of PI and PID controller of Direct FOC Induction Motor Drive. International Journal of Scientific and Research Publications 2012. 2 (7).

55 - Lima Jr. CAS, Lapa CMF, Pereira CMNA., da Cunha JJ, Alvim ACM. Comparison of computational performance of GA and PSO optimization techniques when designing similar systems – Typical PWR core case. Annals of Nuclear Energy, 2011, 38: 1339–1346.

56 - Panda S, Padhy NP. Comparison of particle swarm optimization and genetic algorithm for FACTS-based controller design. Applied Soft Computing, 2008. 8: 1418–1427.

57 - Allen R G, Pereira LS, Raes D, Smith M. Crop evapotranspiration (guidelines for computing crop water requirements). FAO Irrigation and Drainage Paper No. 56. FAO, Rome, Italy. 1998. 290 pp.

58 - Winchell M, Srinivasan R, Di Luzio M, Arnold J. ARCSWAT interface for SWAT2005: User's Guide. 2007. Texas Agricultural Experiment Station and USDA Agricultural Reasearch Service, Temple, Texas. Available at: http://www.geology.wmich.edu/sultan/5350/Labs/ArcSWAT_ Documentation.pdf. Accessed on 2013-02-10.

59 - Environmental Systems Research Institute. 2010. ArcGIS Desktop: Release 10, Redlands, Calif.

60 - Arnold J G, Allen P M, Muttiah R, Bernhardt G. 1995. Automated base flow separation and recession analysis techniques. Ground Water 33(6), 1010-1018.

61 - Arnold J .G, Allen P M. 1999. Automated methods for estimating baseflow and ground water recharge from streamflow records. J. American Water Resour. Assoc. 35(2), 411-424.

62 - NASA and METI– National Aeronautics and Space Administration and Ministry of Economy, Trade, and Industry. 2011. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM data. Available: http://reverb.echo.nasa.gov/reverb/#utf8=%E2%9C%93&spatial_ map=satellite&spatial_ type=rectangle. Accessed on [2012-07-13].

63 - Oliveira JB. Soils from São Paulo State: description of the soil classes registered on the pedologic map. Campinas: Agronomic Institute, 1999, 112p. (Scientific Committee n.45). (In Portuguese: Solos do Estado de São Paulo: descrição das classes registradas no mapa pedológico. Campinas: Instituto Agronômico, 112p. (Boletim Científico n.45)).

64 - Sartori A, Lombardi Neto F, Genovez AM. Classificação Hidrológica de Solos Brasileiros para a Estimativa da Chuva Excedente com o Método do Serviço de Conservação do Solo dos Estados Unidos Parte 1: Classificação. RBRH – Revista Brasileira de Recursos Hídricos, 2005. 10 (4): 05-18.

65 - Saxton KE, Rawls W J. Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. Soil Science Society of Agronomy Journal, 2006 70(5); 1569-1578. DOI: 10.2136/sssaj2005.0117

66 - Molin PG, Miranda FTS, Sampaio JV, Fransozi AA, Ferraz SFB. Mapeamento de uso e cobertura do solo da bacia do rio Piracicaba, SP: Anos 1990, 2000 e 2010. *Circular Técnica IPEF (Instituto de Pesquisas e Estudos Florestais)*. 2015. Available at: http://www.ipef.br/publicacoes/ ctecnica/edicoes.asp. Accessed on 2015-04-01.

67 - ANA - Agência Nacional de Águas. Hydrologic Data – Precipitation and flow historic records. Brasil. 2012. Available: http://hidroweb.ana.gov.br/. Accessed on: 2012-03-10.

68 - DAEE – Departamendo de Águas e Energia Elétrica. Hydrologic Data – Precipitation and flow historic records. São Paulo, Brasil. 2012. Available: http://www.daee.sp.gov.br/. Accessed on: 2012-03-15.

69 - INMET – Instituto Nacional de Meterologia. 2013. Banco de Dados Metológicos para Ensino e Pesquisa (BDMEP). Climate Database for Research and Education. Available on: http://www.inmet.gov.br/portal/index.php?r=bdmep/bdmep. Acessed on: 2013-02-01.

70 - ESALQ/USP – Escola Superior de Agricultura "Luiz de Queiroz"- Universidade de São Paulo. 2013. Meteorological Data. Piracicaba, Brasil. Available: http://www.leb.esalq.usp.br/posto/. Accessed on: 2013-02-10.

71 - Burrough PA, McDonnell RA. Creating continuous surfaces from point data, in: Burrough PA., Goodchild MF., McDonnell RA., Switzer P, Worboys M. (Eds.), Principles of Geographic Information Systems, 1998. Oxford University Press, Oxford, UK, 333pp.

72 - Thiessen AH. 1911. Precipitation for large areas. *Monthly Weather Review* 39: 1082-1084.

73 - Allen, RG, Pereira, LS, Raes, D, Smith, M, Crop evapotranspiration (guidelines for computing crop water requirements). FAO Irrigation and Drainage, 1998, Paper No. 56. FAO, Rome, Italy. p. 290.;

74 - Linacre E, Climate and Data Resources: A Reference and Guide. Routledge, 1992. London. 365p.

75 - Smith, M, CROPWAT, a computer program for irrigation planning and management. FAO Irrigation and Drainage, 1992. Paper 46, FAO, Rome.

76 - Nash JE, Sutcliffe JV. River flow forecasting through conceptual models: Part 1. A discussion of principles. J. Hydrology, 1970. 10(3): 282-290.

77 - Krause P, Boyle DP, Base F. Comparison of different efficiency criteria for hydrological model assessment. Advances in Geosciences, 2005. 5: 89-97. doi:10.5194/adgeo-5-89-2005.

78 - Gupta HV, Sorooshian S, Yapo PO. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. J. Hydrologic Eng. 1999. 4(2): 135-143.

79 - Legates DR, McCabe GJ. Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. Water Resources Res. 1999. 35(1): 233-241.

80 - Moriasi D, Arnold JG, Van Liew MW, Bingner R, Harmel R, Veith TL. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE, 2007. 50: 885-900. doi: http://ddr.nal.usda.gov/handle/10113/9298.

6. *Ensemble Flow Forecasting and Data Assimilation using a Complex Watershed Model and new module for automatic sub-daily calibration*

A modified version of this chapter will be shortly submitted to a peer-review international journal, with the following co-authors: Danielle de Almeida Bressiani, Raghavan Srinivasan, Jairo Rotava, Narumi Abe, Eduardo Mario Mendiondo, Karim C. Abbaspour.

Abstract

Application of hydrological models to watersheds at a sub-daily time step is very important for better understanding of flow and water quality dynamics. The urgency of such applications and developments has increased in recent years due to increased urbanization, and higher frequency of extreme hydro-meteorological events. Climate change impact and accelerated landuse change due to population growth can exasperate the situation in the coming years. Floods impact the greatest number of people, of all natural disasters. An important adaptation strategy to reduce hydro-meteorological risks are the early warning systems. Improved streamflow forecast ability is needed for good early warning systems. Ensemble combination techniques, with probabilistic forecasts have demonstrated improved forecasts. Streamflow forecasting attributed of hydrological semi-distributed models has great appeal for the possibility of forecasts at ungauged locations. Data assimilation is a key element for better flow forecasts, to ensure up to date representations of the state variables. This paper has the aim to provide a framework for streamflow forecasting using ensemble Numerical Weather Prediction (NWP), a semi-distributed process-based hydrological model (SWAT) and data assimilation/inverse modelling with optimization, to support early flood warning systems. Specifically, the objectives of this research are to: (1) develop a new module to allow automatic calibration of flow for SWAT at hourly time-step on SWAT-CUP; (2) assess the sensitivity of different parameters at different time-steps: monthly, daily and hourly and perform one-at-a-time sensitivity analysis of several parameters at hourly time-step; (3) perform SWAT streamflow calibration and validation for a large watershed in southeast Brazil (Piracicaba watershed) at hourly time-step; (4) integrate ensemble numerical weather forecasts as input to hourly and daily

calibrated SWAT models for the Piracicaba River watershed to forecast streamflow for 3 days ahead; (5) develop and test a framework with data assimilation for streamflow forecasting using ensemble NWP, SWAT and SWAT-CUP optimization to support real-time flood warning systems.

Keywords: SWAT-CUP hourly module; Sub-daily SWAT; Ensemble Streamflow Forecasting; Data Assimilation; Piracicaba Watershed.

6-1. Introduction

Of all natural disasters, floods impact on the greatest number of people across the world[1]. An important adaptation strategy to reduce hydro-meteorological risks is the early warning system that allows the government and civil society to take action and reduce the vulnerability and exposure to the risk, isolating or evacuating areas, for example[2,3,4]. Accurate and early warnings for river flooding are essential, and cannot be overestimated[5]. Warning systems are dependent of accurate real-time provision of rainfall data, numerical weather forecasts, operation of hydrological model systems and forecast delivery procedures[6]. The drive to ‘improve’ flood forecasts has risen on the political agenda[4,7,8].

Developing a streamflow forecasting system requires a balance between the need for fast and precise forecasts and a good representation of flow and streamflow wave. Also there is the need to consider the resolution and spatial variability of the watershed and of the weather drivers, the data availability and uncertainties, as well as the computational demand, therefore the need to balance what one wants with what one can have[9]. It includes weather forecasting, hydrological modeling, with upgrading procedures, and associated uncertainties[9,10,11].

The quality of a flood/flow prediction depends to a high degree upon the quality of the measurements and forecasts of precipitation[6]. Therefore large uncertainties are related to the data forecasts and measurements used, and in this paper we demonstrate the limitations of the precipitation gauge network available. Enhancements on the weather forecasts and hydrological models motivate the pursuit of models and model combinations that can improve streamflow forecasts[12] with different resolutions and formulations. Increased computer power is now enabling the operational introduction of high-resolution (a few kilometres grid length) Numerical

Weather Prediction (NWP) models[6]. Improved streamflow forecast ability has been demonstrated through ensemble combination techniques[12,13, 14].

Uncertainty is part of the flood forecasting process. There are errors on the forecasts of hydrologic variables, on the initial and boundary conditions, model and data resolution, and due to the simplification of the physical processes represented on the models[6,15]. Deterministic streamflow forecasts provide users the false impression of certainty[15]. Probabilistic forecasts can be a way of quantifying uncertainty by indicating the likelihood of occurrence of a range of values, enabling decision makers to take risk-based decisions, with potential economic and social benefits[15,16]. Ensemble forecasts can also extend leadtime and better quantify predictability[4] .

Flood forecasting attributed of hydrological distributed grids has great appeal for the possibility of forecasts at ungauged locations, but also to be able to cover a watershed or wide area, with higher levels of data assimilation and the possibility of providing days ahead forecasts[1]. Data assimilation and the use of ensembles are both key elements across disciplines[6]. Most forecasting systems apply data assimilation[5]. The objective is to ensure up to date representations of the state variables, using the most recent available observed data. And then use this new initial state for the subsequent forecasts[5,17].

This paper has the aim to provide a framework for streamflow forecasting using ensemble Numerical Weather Prediction (NWP), a semi-distributed process-based hydrological model (SWAT) and data assimilation/inverse modelling, to support early flood warning systems. Specifically, the objectives of this research are to: (1) develop a new module to allow automatic calibration of flow for SWAT at hourly time-step on SWAT-CUP; (2) assess the sensitivity of different parameters at different time-steps: monthly, daily and hourly and perform one-at-a-time sensitivity analysis of several parameters at hourly time-step; (3) perform SWAT streamflow calibration and validation for a large watershed in southeast Brazil (Piracicaba watershed) at hourly time-step; (4) integrate ensemble numerical weather forecasts as input to hourly and daily calibrated SWAT models for the Piracicaba River watershed to forecast streamflow for 3 days ahead; (5) develop and test a framework with data assimilation for streamflow forecasting using ensemble NWP and SWAT to support real-time flood warning systems.

6-2. Methods

6-2.1. A Sub-daily Watershed Model

Application of watershed models at a sub-daily time step is very important for better understanding of flow and water quality dynamics. Sub-daily processes are determinant for flooding and high extreme events and can also be determinant for river water quality. Therefore it is important to simulate sub-daily events, but also simulating the processes in a continuous capability to realistically capture the watersheds trends and the effects of the sub-daily intense events[18]. The urgency of such applications and developments has increased in recent years due to increased urbanization, and higher frequency of extreme hydro-meteorological events. Climate change impact and accelerated landuse change due to population growth can exasperate the situation in the coming years. The Soil and Water Assessment Tool (SWAT) is internationally accepted as a robust interdisciplinary versatile watershed model, having being applied widely used and applied for hydrological and environmental assessments around the world and was the watershed model chosen for this study[19,20,21,22].

There are very few applications using the sub-daily capabilities of watershed models, in this case SWAT. A modified version of SWAT to accept breakpoint rainfall data and route streamflow on a sub-daily time-step was developed[23]. They also compared the two infiltration methods: SCS daily curve number method (CN) and sub-daily Green-Ampt Mein-Larson (GAML) for a small watershed of 21.3 km^2 in Mississippi, USA. The results were not calibrated, but both methods gave reasonable results for annual, monthly, and daily time steps simulations, but sub-daily time step GAML results were not presented.

Further studies were recommended to use sub-daily rainfall data instead of daily rainfall as major runoff events, and sediment and nutrient losses occur due to very high intensity rain events[24]. ESWAT was developed[25]; a modified SWAT model to perform calculations on a sub-daily time step and included in-stream water quality processes, based on QUAL2E concept. ESWAT was applied to simulate water quantity and quality processes at hourly time step on two different basins in Oklahoma, USA.

Sensitivity analysis and calibration was performed on four different combinations of methodologies within the modelling framework on a small (141.5 ha) watershed in Bedfordshire, UK[26]. They tested two evapotranspiration methods (Hargreaves and Penman-Montieth) with the two infiltration methods for runoff estimation techniques: NRCS curve number (CN) and Green and Ampt. Green and Ampt needs sub-daily rainfall, but was compared on daily time-step. For this study the curve number method performed better than the Green and Ampt method in modelling runoff.

A sub-hourly rainfall–runoff model in SWAT was developed and tested[18]. They modified algorithms related to infiltration, surface runoff, flow routing, impoundments, and lagging of surface runoff. The sub-hourly routines were tested on a 1.9 km^2 watershed in Austin, Texas, USA. A modified physically based erosion models was also included in SWAT for seamless modeling of erosion processes with the recently developed sub-hourly flow models and algorithms for simulation of stormwater best management practices (BMPs)[27]. The modified SWAT sub-daily model was calibrated and validated for flow and sediment for small watersheds in Texas, presenting good results.

An evaluation of SWAT sub-daily runoff estimation was done for a small field-size (0.8 ha) agricultural watershed in South Korea**[28]**, the results for calibration and validation were very good, whereas the simulation results using daily rainfall data were out of acceptable limits for the model simulation. SWAT sub-daily with hourly precipitation and Green & Ampt infiltration method was proven efficient for runoff estimation at field sized watershed with higher accuracies that could be efficiently used to develop site-specific Best Management Practices (BMPs) considering rainfall intensity, rather than simply using daily rainfall data. Boithias et al.[29] assessed the ability of the SWAT model to simulate discharge at hourly time-step in the ~1,400 km^2 Têt Mediterranean river basin (southwestern France) and compared model's performances when using different resolutions on grids of climate stations and sub-basins representation.

Few models are capable of simulating water resources processes at a watershed scale and with sub-daily time steps to be able to describe flash and intense events, and continuous simulation capability to realistic capture the long-term trends in water quantity and quality processes that are experiencing land use changes (urbanization increases), more intense and frequent extreme events and flooding, and possible effects of climate change. As shown SWAT has this capability, but its sub-daily algorithms are still recent, and have not been tested in large watersheds, to assess specific events and flooding and at the same time provide a framework for whole watershed simulation and understanding of processes. The SWAT sub-daily modules are done through sub-daily rainfall, Green & Ampt infiltration method and hourly routing. Details on the new SWAT formulations of the sub-daily and sub-hourly modules can be found at Neitsch et al.[30] and Jeong et al.[18].

6-2.2. Piracicaba Watershed Hourly SWAT Model set-up

The Piracicaba Watershed ArcSWAT project set-up was already described on Chapter 4 and 5[31]. The ArcSWAT calibrated Piracicaba model with SUFI2 for the three gauge stations and daily time-step was used for the set-up of the hourly SWAT Piracicaba model. The only difference related to data input to the model, was that from daily precipitation, hourly precipitation was used.

Precipitation is the major driving force of a hydrologic model. Large uncertainties were introduced with this decrease on the simulation time-step, since there was a lot less available data at the hourly time-step, then at daily. From close to two hundred daily precipitation gauge stations, that were interpolated for each sub-basin for a period of ~35 years, for sub-daily data input we only had available data from 16 gauge stations (Figure 6-1) (not well spatially distributed over the watershed) with reasonable data for one to seven years, depending on the station. Also many problems and inconsistent precipitation data was found on the data series.

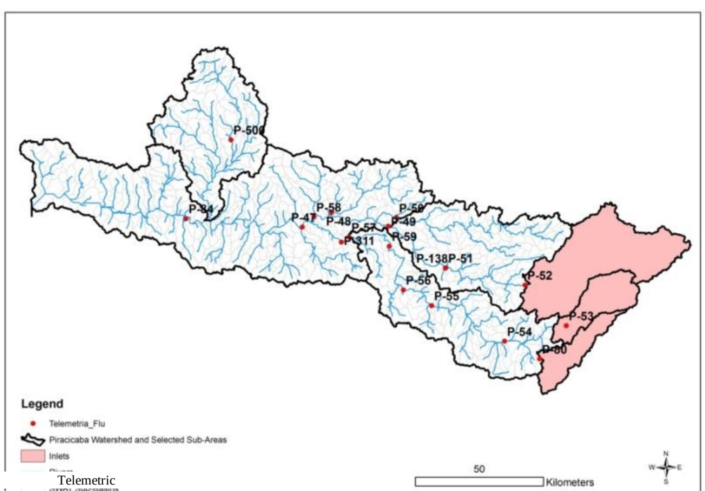


Figure 6-1 - Piracicaba Watershed and precipitation and streamflow sub-daily gauge stations

The sub-daily precipitation data on the first few years was in a time-step of 3 hours and after at a ten minutes time step. Therefore the first years were only used for model warm-up and they were subdivided in hourly time-step, using a triangle base (first hour 25% of precipitation, second: 50% and third: 25%), and the ten minute interval was aggregated in hourly time-steps. The data processing was done on Matlab. The major outlines (clear measurement errors) from the precipitation and flow records were taken off of the data series. The precipitation records from the sixteen gauge stations were interpolated to establish one complete series per gauge station. The interpolation was by Inverse Distance Weighted (IDW)[32], with the PCP_SWAT ArcGIS plug-in program[33] up to 2012, and after a Matlab code was done, also using IDW. With the complete new series for each station the input precipitation files to ArcSWAT were changed: therefore the pcp.pcp file of SWAT model was changed with hourly inputs.

For sub-daily simulation, other than the precipitation input, it is also necessary to change a few SWAT model inputs related to the methods used. The IDT variable, related to sub-daily rainfall data time step on the 'file.cio' was changed to 60 minutes. The IEVENT variable, related to the infiltration method used, located on the file 'basins.bsn', was changed on the new SWAT version and also needs to be changed. Now on the newer version of SWAT there are two possibilities: daily rainfall with SCS modified curve number technique (which receives the value of zero, 0) and sub-daily rainfall with Green & Ampt method and hourly routing (with the value of 1), therefore for daily outputs we run the model with IEVENT of zero, and for hourly we run it with IEVENT of one.

Up to the moment, a custom specific command has to be added on the 'fig.fig' file to extract the hourly outputs for selected sub-basins on SWAT in separate files. The command is 'saveconc' and it can be added in the end of the file before the 'finish'. For more information on how to change the fig.fig file one can refer to the SWAT Input/Output File Documentation (Chapter 2: SWAT Input Data: Watershed Configuration) and to the SWAT-CUP hourly 'manual' developed.

6-2.3. Automatic Sub-Daily Calibration (SWAT-CUP new sub-daily module)

A new module was done to allow automatic calibration for flow and sediment at hourly time-step with different possibilities of objective function (nine possibilities), as also multi-objective and multi-site calibration. This was done using the already established SWAT Calibration Uncertainty Procedures (SWAT-CUP) software[34]. It is possible to perform sensitivity analysis, calibration, validation, and uncertainty analysis using the Sequential Uncertainty FItting (SUFI-2) algorithm[34,35]. A new component to extract the data from the different sub-daily output format from SWAT was incorporated into SWAT-CUP to allow comparison with the observed data. Also the previous executables were compiled to be able to run for a larger number of comparison points.

For the Piracicaba watershed after a yearly comparison, monthly and daily calibrations and validations[31], with the daily calibrated parameters as "initial condition" the hourly calibration was performed. Therefore first a global sensitivity analysis was done. The hourly global sensitivity analysis results were compared with monthly and daily ones, in terms of P-Values[31,35]. To understand better the sensitivity of each parameter at hourly time step a local sensitivity analysis was also performed [31,36,37,38]. Therefore one parameter at a time was changed and four iterations were ran for each parameter in a defined range. This sensitivity analysis was performed for twenty four parameters with wide ranges: presented in Table 6-1 and they were assessed in terms of absolute change in Nash-Sutcliffe values (NSE)[40].

One parameter (Surlag) was assessed in two ranges, since it was expected it had higher sensitivity for smaller values, based on previous daily calibration experience and on the fact that a new lag equation was inserted for sub-daily SWAT processes, since in smaller time intervals it is also expected that a smaller portion of the excess rainfall reaches the main channel[18]. Flow calibration was performed for two years: for 2011 and 2012, since the later years had better data, but at the same time the years 2013 and 2014 were drought years, therefore we did not want to calibrate the model with those years. The calibration was done first for gauge station P-59, at sub-region A1 (at the same location as in for daily calibration, Chapters 4 and 5), then for the most downstream gauge station: P-84 (again close to the same location calibrated for daily). The objective function for calibration was based on Nash-Sutcliffe[40]. The calibration results were assessed based on NSE, which varies from -∞ to 1, being 1 the ideal fit between observed and predicted; Percent Bias (PBias) [41], with zero as the ideal best fit solution and larger absolute values tending to worse results; coefficient of determination (R^2), ranges from 0 to 1, with higher values indicating less error variance; and r-factor and p-factor[35,42], in which p-factor ranges between 0 and 100%, and r-factor between 0 and ∞. A P-factor of 1 and R-factor of 0 would correspond to an exact simulation; a balance between the two is desirable. Cross-validation and validation was performed for all the other gauge stations with data, for different time periods.

6-2.4. Probabilistic Flood Forecasting with Ensemble Data

Numerical Weather Prediction (NWP) systems have advanced significantly on improved estimates of precipitation quantity, timing and spatial distribution. The question is how this improvement can yield meaningful flood forecasts for given basins, meteorological events and prediction products. Operational flood forecasting systems are moving towards the adoption of ensembles of NWPs, rather than single deterministic forecasts[4]. Similar studies on streamflow forecasting have been developed in Brazil, using different models and sources of precipitation forecasts[43-50]. The studies presented good results and also that there is still room for improvement.

This paper uses the ensemble numerical weather predictions from the Eta model [51,52] that has been developed and for weather prediction at the Brazilian Center for Weather Forecasts and Climate Studies (Centro de Previsão de Tempo e Estudos Climáticos, CPTEC), of the National Spatial Research Institute (INPE). It provides operational weather forecasts over most of South America since late 1996[53]. It has also been used to study extreme events associated with disasters [54-57].

Table 6-1 - Parameters and ranges selected for One-at-a-time sensitivity analysis for SWAT at hourly time step

Type of Change[a]	Parameter Name and file	Parameter Description	Ranges Min.	Max.
R	ALPHA_BF.gw	Base flow recession constant	-0.2	0.2
V	CANMX.hru[b]	Maximum canopy storage (mm)	0	25
R	CH_K1.sub	Effective hydraulic conductivity in tributary channel alluvium (mm/hr)	-0.3	0.3
R	CH_K2.rte	Effective hydraulic conductivity in main channel alluvium (mm/hr)	-0.4	0.4
R	CH_L1.sub	Longest “tributary” channel length in subbasin (km)	-0.25	0.25
R	CH_N1.sub	Manning's "n" value for tributary channels	-0.25	0.25
R	CH_N2.rte	Manning's "n" value for the main channel	-1.0	+1.0
R	CH_S1.sub	Average slope of tributary channels (m/m)	-0.25	0.25
R	CN2.mgt	SCS Curve Number (moisture condition II)	-0.4	0.4
V	ESCO.hru	Soil Evaporation compensation coefficient	0.6	0.95
A	GW_DELAY.gw	Groundwater delay time(days)	-90	30
V	GW_REVAP.gw	Groundwater "revap" coefficient	0.02	0.09
A	GWQMN.gw	Threshold depth of water in the shallow aquifer for return flow to occur (mm)	-1000	130
R	HRU_SLP.hru	Average slope steepnes (m/m)	-0.25	0.25
V	LAT_TTIME.hru	Lateral flow travel time (days)	0	25
R	OV_N.hru	Manning's "n" value for overland flow	-0.3	0.3
V	RCHRG_DP.gw	Aquifer percolation coefficient	0.01	0.095
A	REVAPMN.gw	Threshold depth of water in the shallow aquifer for revap to occur (mm)	-500	500
R	SLSUBBSN.hru	Average slope length (m)	-0.25	0.25
R	SOL_AWC.sol	Soil available water capacity	-0.4	0.4
R	SOL_K.sol	Saturated hydraulic conductivity (mm/hr)	-0.5	0.5
V	SURLAG.bsn	Surface runoff lag coefficient	0.0001	0.1
V	SURLAG.bsn	Surface runoff lag coefficient	0.0001	12
V	CNCOEF.bsn	Plant ET curve number coefficient	0.5	1

a- R indicates a relative change (percentage), V replaces the value of the parameter, and A is an addition (adding to SWAT’s default value);

b- Only for forest.

The Eta model chosen has a spatial resolution of a 5km grid, and has 5 members of ensemble. The model is generated two times a day, at 00 and 12 UTC, and has a forecast horizon of 3 days ahead, with hourly time-step resolution. The five members were developed with different combinations related to physics methods. Includes two convection schemes: Betts-Miller-Janjic[58,59], and Kain-Fritsch[60]; cloud microphysics processes: Zhao or Ferrier[61]; and boundary conditions from: the predictions of the Eta-40km/CPTEC model, or from the National Centers for Environmental Prediction's (NCEP) Global Forecast System (GFS). The ensembles started to be generated in March, 2013.

The Ensemble Eta model outputs for the entire South America were provided by the Supercomputing Service from CPTEC/INPE by ftp. The Eta model data comes on Grid Analysis and Display System (GrADS) format, which is a computational interactive tool for analysis and exhibition of earth science data[62]. Scripts on Linux and OpenGrADS (http://opengrads.org/) open the Eta GrADS files and extract the weather variables of interest by grid cell and write them into text files by day. Then a Matlab script was written to check if the runs are complete, and another to take the information from the center of the closest grid to each SWAT subbasin centroid and converts it into SWAT files format.

6-2.6. Data Assimilation for a better forecast

Data assimilation is a key element of real time flood forecasting (Madsen et al., 2000). The objective of data assimilation is to use the most recent observed data to ensure an up to date representation of the models state variables[5,6], to enhance the model reliability and reduce predictive uncertainties[17]. Since the reliability of hydrological models is affected by limited measurements and imperfect models[17] and errors in initial conditions tend to grow rapidly[6] and have important impact on the anticipated lead time[4]. This kind of data assimilation can also be called inverse modelling, which consists of using measurements to infer the values of the parameters that characterize the system[63].

Normally data assimilation is performed by interpolation, smoothing or filtering[64,65]. Data assimilation involve generating new estimates of input data and parameters updated and their inclusion on the hydrological model, so that, by trying to generate better input data, better forecasting is performed[66]. Hydrological data assimilation deserves much more attention than what currently has, in particular in science to better represent the heterogeneity of sub-grid scale[4]. Combined parameter optimization and sequential data assimilation has been proposed and applied in hydrological modeling to improve treatment of input, output, parameter and model structure errors[67].

In this paper we opted to use a combined approach of optimization with data assimilation. We are using the precipitation and streamflow data from the telemetric gauge network from SAISP and DAEE-CTH/FCTH. The calibrated and validated hydrological SWAT model is ran up to a given day or hour. In order to reduce the errors before the forecast the measured streamflow is used to update state variables: sixteen data points of flow are used to optimize SWATs main inputs (precipitation) using SUFI-2 algorithm in SWAT-CUP and therefore all the state variables of the model are updated at once. This updated model, with flow values closer to the observed ones, is then used to forecast streamflow with the ensemble NWP ETA model data for the next three days in the future. In Figure 6-2 the flow chart of the process is shown. The automation was done in Bash and Python in Linux operational system.).

To present the idea in a simplified form for the thesis, one event was chosen, and the optimizations in SWAT-CUP were conducted for each day for 2 iterations of twelve runs each, the first starting with a range of –15mm to +15 mm of precipitation that could be added or subtracted from the observed data, and for the second iteration the suggested new range from SUFI2 was used. The comparison was done only for the most downstream gauge station P-84, the precipitation of the past four days were updated to then forecast the following three. Only the daily model was used so far, since the change in precipitation data inputs is only supported on the daily SWAT-CUP version. For this first implementation only precipitation was accounted for, since the main focus of this study is flooding. But in future work, other parameters, as state variables could also be inserted in the structure, optimizing for example variables related to in-stream processes, for low flow periods, as variables related to groundwater storage and soil properties: as for example the available water capacity in the soil layers or saturated hydraulic conductivity, but further work must be conducted on testing this theory and better way of implementating it.

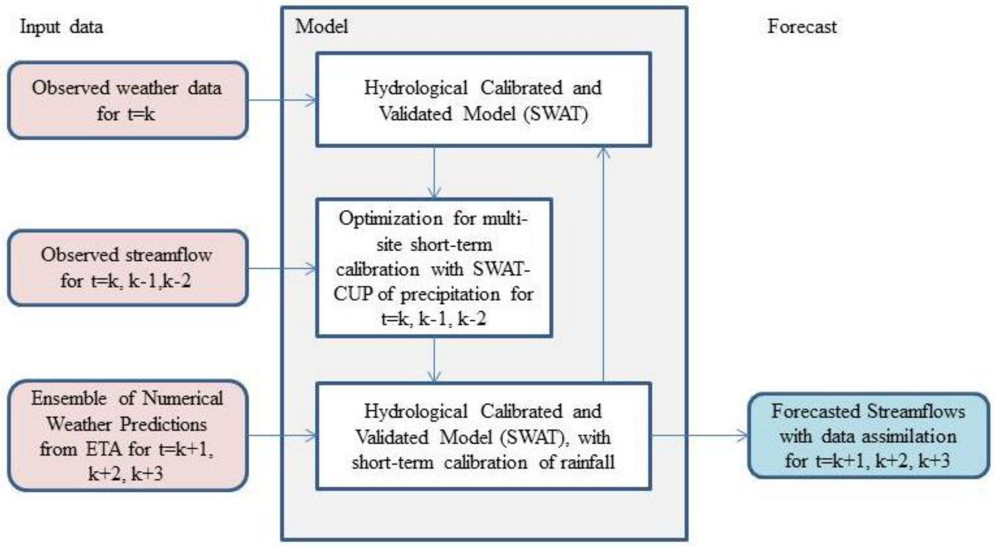


Figure 6-2 - Flow Chart of the streamflow forecasting process

6-3. Results and Discussion

6-3.1. Global Sensitivity Analysis

The results for the sensitivity analysis for monthly, daily and hourly time-steps are summarized at Table 6-2, the most sensitive parameters (with P-values closer to zero) for each time-step are highlighted. The results are different than the ones presented by Jeong et al.[18]. The SCS Curve Number (CN2) was the most sensitive parameter for all the three different time-steps' simulations. CNs related coefficient (CNCOEF) was right behind CN2 in sensitivity for daily and hourly, for monthly its sensitivity was not assessed. For monthly time-step the second most sensitive parameter was related to groundwater processes: GW_Delay. For the daily time-step other than CN2 and CNCOEF, the coefficient related to soil evaporation (ESCO) was also very sensitive. Processes related to timing of the hydrographs were also sensitive for daily and hourly time-step: as lateral flow travel time (LAT_TTIME) and surface runoff lag coefficient (SURLAG) that were very sensitive for daily time step (together with soil available water content: SOL_AWC). LAT_TIME was also very sensitive for hourly time-step, and SURLAG showed to be more sensitive when a one at a time sensitivity analysis was performed.

6-3.2. One at a Time Sensitivity Analysis

The results for the local sensitivity analysis are summarized for the 15 most sensitive parameters (with NSE absolute variation above 0.01) in Table 6-3. The most sensitive parameters were curve number (CN2), Manning's "n" value for the main channel (CH_N2), surface runoff lag coefficient (SURLAG), pant ET curve number coefficient (CNCOEF), groundwater delay time (GW_DELAY), saturated hydraulic conductivity (SOL_K), lateral flow travel time (LAT_TTIME), soil available water capacity (SOL_AWC). The parameters involved in the GAML equation appeared, as expected, as the most sensitive ones: CN2, SOL_K and SOL_AWC. Parameters related to the hydrographs timing and channel routing also were very sensitive, as CH_N2, Surlag and LAT_TIME.

Table 6-2 - Sensitivity of SWAT parameters for different time intervals (monthly, daily and hourly)

	P-Value		
Parameter Name	Monthly	Daily	Hourly
ALPHA_BF	0.25	0.54	0.13
CANMX	--	0.70	0.72
CH_N1	--	0.84	0.78
CH_N2	0.34	1.00	0.17
CN2	**0.10**	**0.00**	**0.00**
CNCOEF	--	**0.00**	**0.04**
ESCO	0.90	**0.00**	0.13
GW_DELAY	**0.00**	0.99	0.54
GW_REVAP	0.12	0.27	0.48
GWQMN	0.97	0.65	0.90
HRU_SLP	--	0.40	0.69
LAT_TTIME	--	**0.01**	**0.06**
OV_N	--	0.98	0.70
RCHRG_DP	0.27	0.17	0.79
REVAPMN	0.73	0.29	0.60
SLSUBBSN	0.53	0.24	0.36
SOL_AWC	0.52	**0.01**	0.99
SURLAG	0.84	**0.01**	0.41

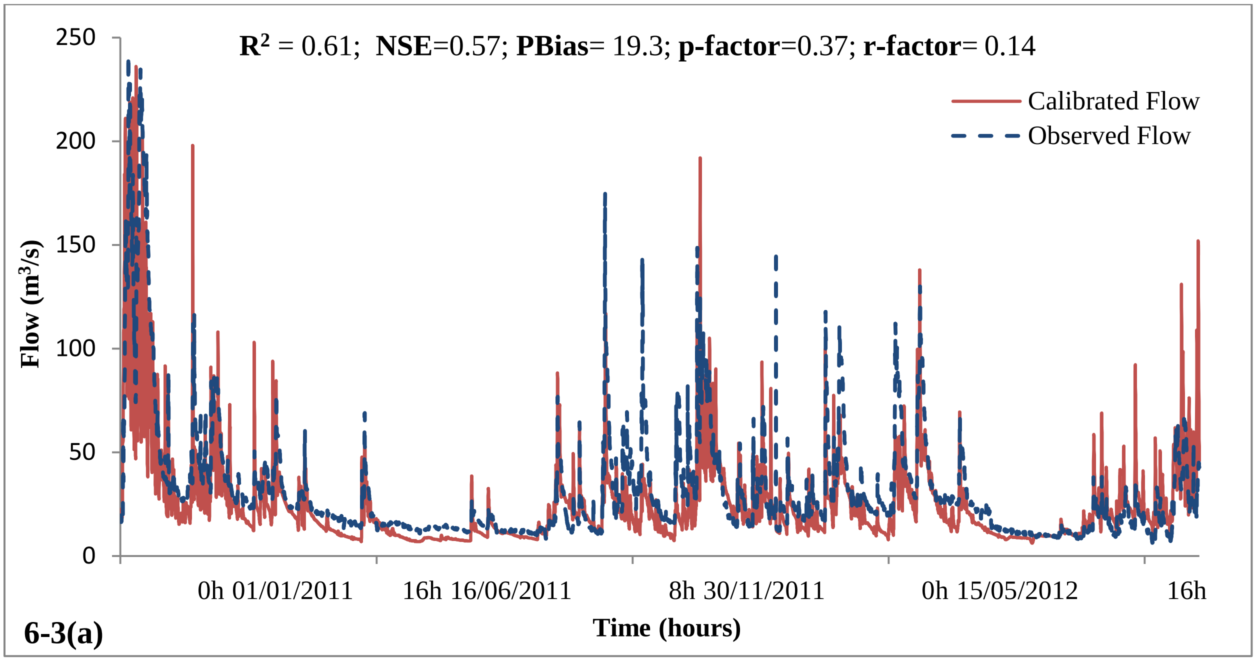
Table 6-3 - One at a Time Sensitivity Analysis: Fifteen SWAT most sensible parameters at hourly time-step

Rank	Parameter Name	NSE Absolute Variation
1	CN2	0.670
2	CH_N2	0.520
3	SURLAG [a]	0.147
4	CNCOEF	0.132
5	GW_DELAY	0.119
6	SOL_K	0.117
7	LAT_TTIME	0.098
8	SOL_AWC	0.058
9	ESCO	0.045
10	HRU_SLP	0.027
11	OV_N	0.026
12	CH_L1	0.018
13	CH_N1	0.013
14	CANMX	0.011
15	RCHRG_DP	0.010

[a] – Smaller interval variation of Surlag (in between 0.0001 and 0.1)

6-3.3. Calibration and Validation

The hourly stream flow hydrographs for model calibration predictions and measured data are presented in Figure 6-3(a) for gauge station P-59, at sub-region A1 and (b) for the most downstream gauge station: P-84. The statistic values are reasonable, especially considering the precipitation data limitation. The NSE values are above 0.5, considered satisfactory by performance metrics classification from Moriasi et al.[68] PBias values were considered very good for gauge station P-84 and satisfactory for gauge station P-59, R^2 values were also considered good[68]. For the first calibrated gauge station R-factor value is closer to zero, while P-factor is smaller and for the downstream gauge station both have intermediate values. Also by looking at the hydrographs the calibrated model follows well the observed behavior, in the timing and also reaching most of the peaks, although it is not as smooth as the observed hydrographs, especially for gauge station P-59.



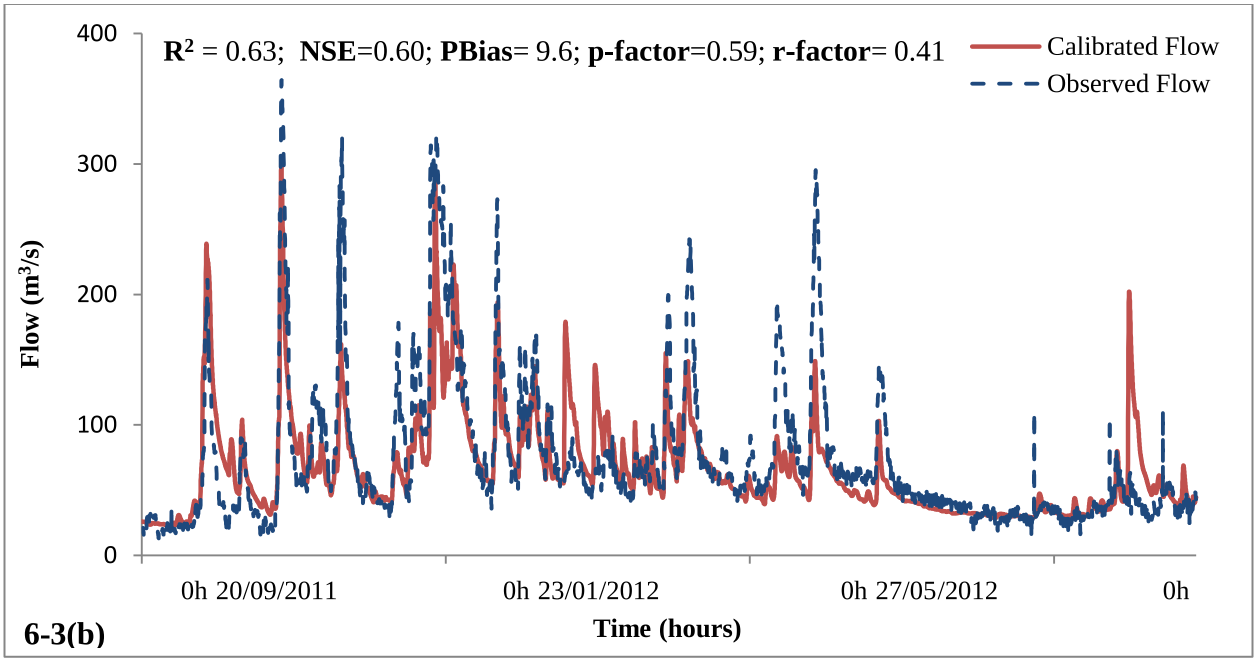


Figure 6-3 - Hourly Calibrated and Observed Flows (a): for Gauge Station P-59 (sub-region A) and (b): for Gauge Station P-84 (sub-region C)

The calibrated parameters are presented in Table 6-4, the relative values for gauge station P-59 are based on the daily calibrated values and for P-84; they are relative to the previous calibration at P-59. The timing and routing parameters and the Green & Ampt SWAT related parameters were the most sensitive and the ones used for calibration: as the channel related parameters, soil available water capacity and hydraulic conductivity, as well as curve number and the CNCOEF. Although some parameters seem to have had a large relative change, some of the values of Manning's "n" (CH_N2 and OV_N) for example were low, therefore they are still within reasonable values. CN2 values estimated with SWAT using Green & Ampt were considered high in comparison with the CN2 values estimated for daily with SCS Curve Number method. As also even though some parameters may be over the ranges that usually are used for daily, we decided to focus on the results, since there are several model and data limitations and uncertainties related to the hourly SWAT Piracicaba model.

Table 6-4 - Calibrated Parameters

Type of Change[a]	Parameter Name	P-59	P-84
R	CH_N2	1.99	0.11
V	SURLAG	0.01	
R	SOL_AWC	0.68	-0.10
R	SOL_K	0.66	
R	SLSUBBSN	-0.25	0.04
R	HRU_SLP	0.19	-0.05
V	ESCO	0.75	0.77
V	LAT_TTIME	9.23	
R	ALPHA_BF	0.02	0.43
A	GW_DELAY	6.77	-54.50
R	CN2	-0.41	0.03
V	CNCOEF	0.53	
R	CH_L1	--	0.08
R	OV_N	--	2.72

[a]- R indicates a relative change (percentage), V replaces the value of the parameter, and A is an addition (adding to SWAT's default value);

The validation period for gauge station P-59 was from 06/01/2008 to 12/31/2010 and from 01/01/2013 to 10/31/2014, a total of 37,127 hourly data points of streamflow were compared. The results found were considered good for the entire time period, with NSE values of 0.52; R2 of 0.62; and PBias of 13.9. Validation was performed on gauge station P-84 from 01/01/2013 to 10/31/2014: 15,834 data points were used. Validation for P-84 also yielded good statistical results for the comparison of hourly streamflow with NSE value of 0.57; R2 of 0.82 and PBias of 25.8.

The cross-validation results are presented in Table 6-5 for twelve gauge stations, the number of hourly streamflow data points compared is also presented (n- data points), as the NSE, R^2 and PBias values. Most of the gauge stations, around five, were considered to have very good results for the entire time period. Some stations had regular results, with NSE values around 0.4; and three gauge stations were considered not good, with NSE values below 0.3. P-56 did not have good results, but the upstream gauge stations P-55 and P-54 and the downstream calibrated station P-59 and more downstream station P-57 had better results. P-51 also did not have good results, but the downstream gauge P-49 had excellent results. P-311 had similar situation, having bad results, but being very close to gauge station P-57, which yielded satisfactory results. Sub-region A3 and C had very few gauge stations and therefore the precipitation patterns from these regions were not inserted in the model, therefore we did not expect very good results from gauge stations P-50 and P-500.

Table 6-5- Cross-Validation Results

Gauge Stations	n (Data Points)	NSE	R2	PBias
P-54	55,916	0.56	0.57	2.5
P-55	54,776	0.41	0.54	24.1
P-56	55,060	0.39	0.48	24.0
P-57	54,033	0.49	0.63	21.7
P-51*	31,643	0.39	0.54	32.5
P-49	38,952	0.74	0.82	25.9
P-50	42,729	0.29	0.52	42.1
P-58	55,930	0.58	0.82	38.3
P-47	33,251	0.56	0.73	28.0
P-311	26,549	0.29	0.49	31.9
P-48	47,808	0.60	0.76	31.3
P-500	19,893	0.21	0.27	19.7

*Same gauge station as P-138

6-3.4. Ensemble Streamflow Forecasting

The results for ensemble streamflow forecasting will be presented for one of the largest events in 2013 (year in which we have ETA data). The results presented start for 3/31/2013 only for the simulated streamflow data with observed precipitation, and for the observed flow data, they continue until 4/18/2013. Then in 04/01/2013 there is the first presented forecast for three days ahead wih the five ETA ensembles simulated in SWAT, and for each day a new forecast with the five members was done.

The streamflow simulated results with observed rainfall data, the forecasted streamflows with the five members from the ETA model for three days ahead, as well as the observed flows are presented for daily (Figure 6-4) and hourly (Figure 6-5) time-steps (a) for gauge station P-59, at sub-region A1 and (b) for the most downstream gauge station: P-84.

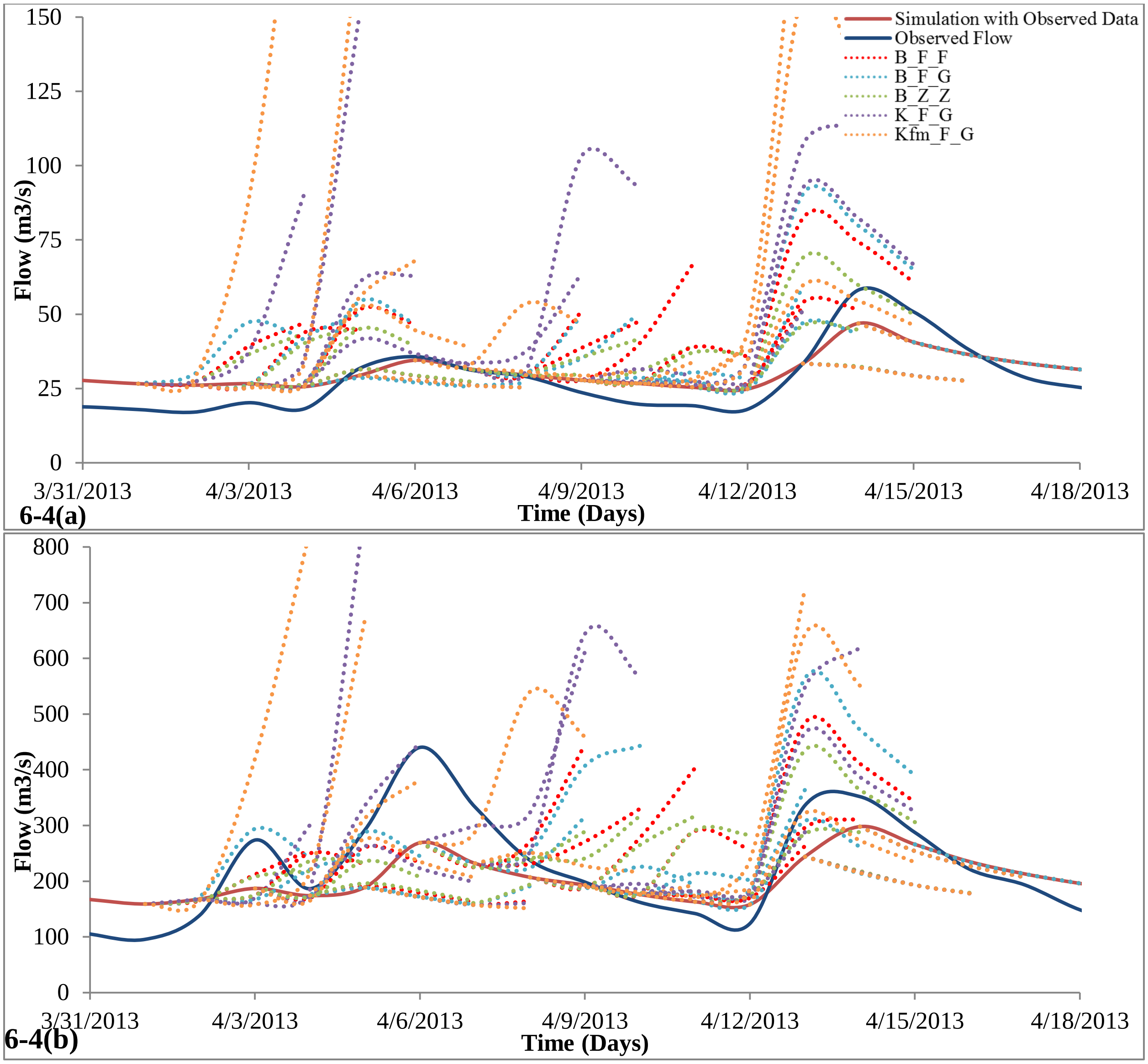


Figure 6-4 -Ensemble daily streamflow forecasting with ETA model data (a): for Gauge Station P-59 (sub-region A) and (b): for Gauge Station P-84 (sub-region C). Observed flows are in blue and simulated SWAT flows with observed precipitation are in red; the five members from the ETA model simulated in SWAT are presented in dashed lines.

The flow forecasts with the ETA model members present an indicative of when the streamflow will rise. When a greater number of members of the same day and previous days indicate a similar pattern the confiability of the results seems greater. The ETA model, for most of its members, seem to forecast precipitation with some lag, and therefore forecasting the flow to rise before it actually happens. The members Kfm-F-G and K-F-G seem to be overstimating more, althought for example for the peak at 4/6/2013 at the gauge station P-84 the best estimation was with K-F-G. Overall there are large uncertainties in NWPs and at the ETA model ensemble products, but these forecasts can give important indicatives.

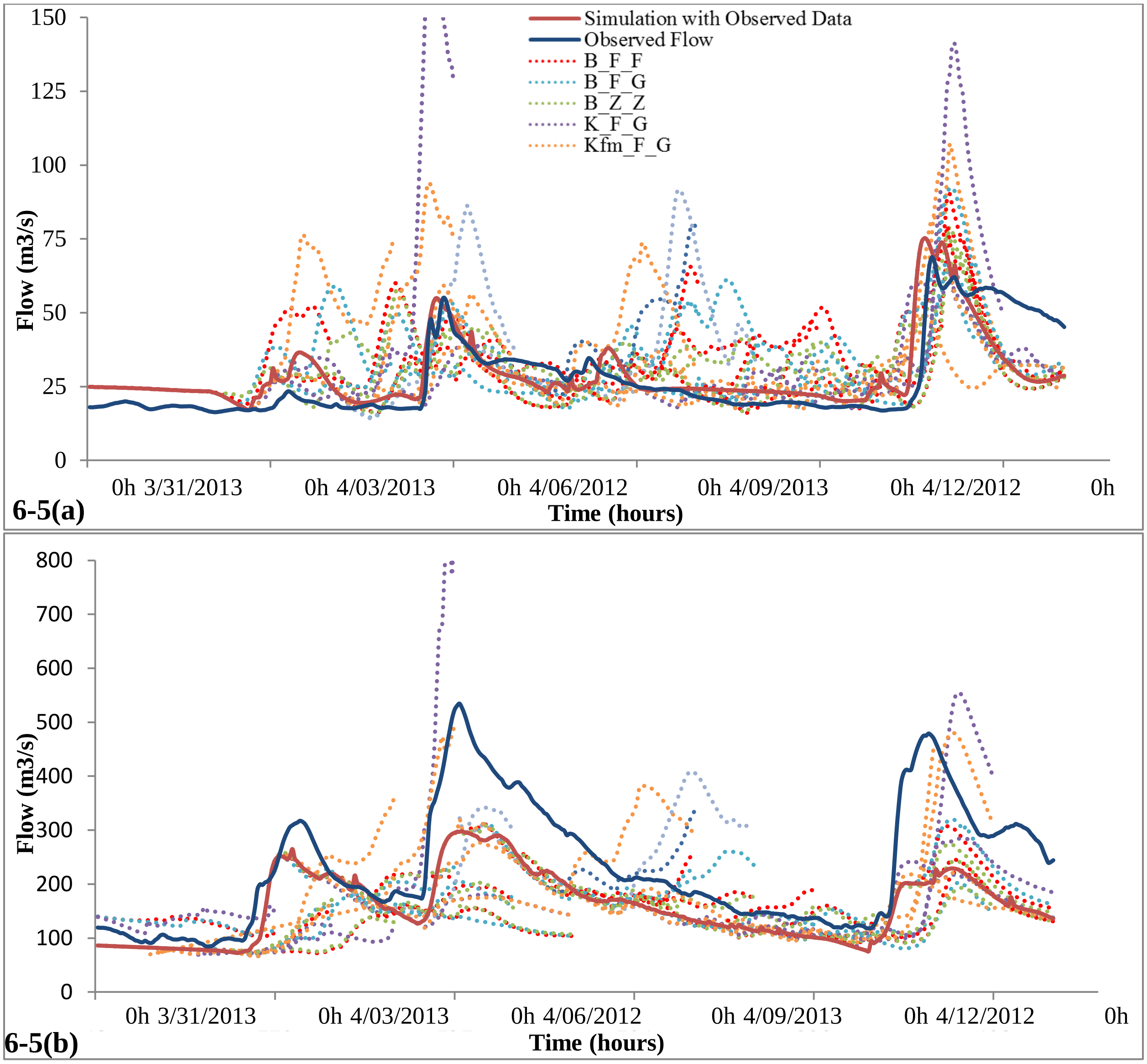


Figure 6-5 -Ensemble hourly streamflow forecasting with ETA model data (a): for Gauge Station P-59 (sub-region A) and (b): for Gauge Station P-84 (sub-region C). Observed flows are in blue and simulated SWAT flows with observed precipitation are in red; the five members from the ETA model simulated in SWAT are presented in dashed lines.

The hourly streamflow forecasts with ETA ensemble data present a better indicative than the daily ones. It has a good tendency for the peaks, when most of the members (generated in different time steps) converge in similar ranges. It presents a better hydrograph timing and the absolute forecasts values have smaller absolute differences in relation to the observed.

6-3.5. Data Assimilation for a better forecast

The results for ensemble streamflow forecasting with data assimilation are presented in Figure 6-6, for the same event already presented, for daily time-step for the most downstream gauge station: P-84. The last four days of streamflow observed data are used for data assimilation, by optimizing the simulated SWAT run with SUFI2 in SWAT-CUP, changing the input precipitation of the last four days. Then, to run the ensemble ETA forecasts to forecast streamflow, based on the data assimilated model for when this is closer to the observed data, or using the simulated without data assimilation when this one is better.

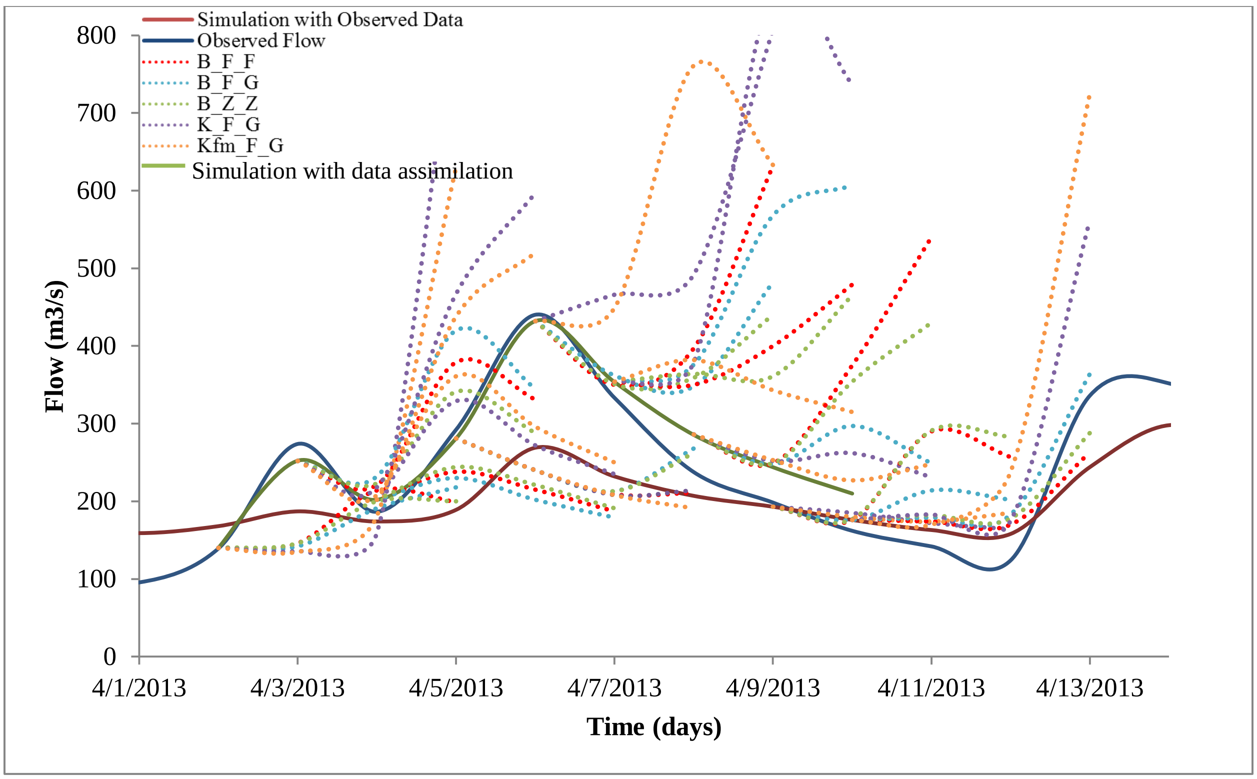


Figure 6-6 - Data Assimilation example for one event with ensemble daily streamflow forecasting with ETA model data for Gauge Station P-84. Observed flows are in blue and simulated SWAT flows with observed precipitation are in red; the simulation with data assimilation is in green; and the five members from the ETA model simulated in SWAT.

The data assimilation process showed very promising results. It had a very fast improvement for the flow simulation, which reached results a lot closer to the observed data for the first days, prior the event and during the event, therefore reducing the first gap on the "current" date to start the forecast. This can be of much help on operational forecasting systems, in which this type of gaps can lead to worst forecasts. Therefore with the data assimilation model the uncertainties on the start date for the forecasts decrease, leaving most uncertainties to the weather predictions. One can see that the model simulation with data assimilation (green line) is a lot closer than the previous simulation with observed precipitation.

For each presented day two iterations of 12 runs were performed to optimize the data and perform inverse modelling, these simulations were done in a Server with 12 CPUs and both take an average of 20 minutes, therefore depending on the computational resources; more simulations can be performed. It is possible to see that after the peak, on the end of the recession curve, for this example, the model with assimilated data performed worse than the previous simulation with observed precipitation, this is because the increase in precipitation occurred before hand, and precipitation cannot be decreased below zero. One alternative can be to increase the number of precipitation days to be changed, to be able to better address such issues. Other way of dealing with this, would be to incorporate other state variables in this optimization process, including parameters related to soil characteristics or groundwater storage on the system, therefore, being able to reduce the simulated flow. For now, for this point, since the model without data assimilation was better, it was used for the ensemble forecast.

6-4. Conclusions

We believe this paper has several contributions to the modelling community. This paper provided a framework for streamflow forecasting using ensemble Numerical Weather Prediction (NWP), a semi-distributed process-based hydrological model (SWAT) and data assimilation/inverse modelling, which can be used to support streamflow forecasting, and, therefore to early flood warning systems. This paper presented a new module to allow automatic calibration of flow for SWAT at hourly time-step on SWAT-CUP; assessed the sensitivity of different parameters at different time-steps: monthly, daily and hourly and perform one-at-a-time sensitivity analysis of several parameters at hourly time-step, showing that the most sensitive parameters were parameters involved in the GAML equation appeared, as expected, as the most sensitive ones: CN2, SOL_K and SOL_AWC, and parameters related to the hydrographs timing and channel routing, as CH_N2, Surlag and LAT_TIME.

The SWAT results for hourly modeling calibration and validation, as well as cross-validation, considering the large uncertainties on data inputs, especially reduced hourly data precipitation gauges, for a large watershed in southeast Brazil were considered satisfactory. Ensemble forecasts from the ETA model were integrated as input to the hourly and daily validated SWAT models successfully, although there are clear and large uncertainties, especially on the meteorological forecasts, it seems that when most members forecast in the same range, the reliability increases. A framework for data assimilation through optimization using SUFI2 and SWAT-CUP was developed and one example was presented demonstrating the increase in performance of the SWAT model related to data assimilation, and therefore being able to provide more reliable forecasts. This developed method foresees future applications which can help the real time operational decision making for disaster risk reduction of hydrological extremes at strategic river basins

6-5. Acknowledgements

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6-6. References

1 - Robert JM, Bell VA, Jones DA. Forecasting for flood warning. C. R. Geoscience. 2005, 337: 203–217. DOI:10.1016/j.crte.2004.10.017.

2 - UNISDR (United Nations International Strategy For Disaster Reduction)/Platform for the Promotion of Early Warning, Four Elements of People Centered Early Warning Systems, presented at the Virtual Symposium, Public Entity Risk Institute: Early Warning Systems – Interdisciplinary Observations and Policies from a Local Government Perspective. April 18-22, 2005.

3 - Penning-Rowsell E, Tunstall S, Tapsell S, Parker D. The benefits of flood warnings: real but elusive, and politically significant. Journal of the Chartered. Institution of Water and Environmental Management. 2000, 14, 7–14.

4 - Cloke HL, Pappenberger F. Ensemble flood forecasting: A review. Journal of Hydrology. 2009, 375, 613–626.

5 - Weerts AH, Serafy GYE, Hummel S, Dhondia J, Gerritsen H. Application of generic data assimilation tools (DATools) for flood forecasting purposes. Computers & Geosciences. 2010, 36, 453–463.

6 - Collier CG. Flash flood forecasting: What are the limits of predictability? Quarterly Journal of the Royal Meteorological Society. 2007, 133, 3–23. DOI: 10.1002/qj.29

7 - Demeritt D, Cloke H, Pappenberger F, Thielen J, Bartholmes J,Ramos M-H. Ensemble predictions and perceptions of risk, uncertainty, and error in flood forecasting. Environmental Hazards. 2007, 7 (2), 115–127

8 - DKKV, 2004. Flood Risk Reduction in Germany. Lessons Learned from the 2002 Disaster in the Elbe Region. Summary of the Study. Deutsches Komitee fuer Katastrophen vorsorge (DKKV) (German Committee for Disaster Reduction). Publication 29e. Bonn.

9 – Rabuffetti D, Barbero S. The hydro-meteorological chain in Piemonte region, North Western Italy - analysis of the HYDROPTIMET test cases, Natural Hazards and Earth System Sciences, 2005, 5, 845-852.

10 - Toth Z, Talagrand O, Candille G, Zhu Y. Probability and ensemble forecasts. In: I.T. Joliffe & D.B. Stephenson, eds. Forecast verification: a practitioner’s guide in atmospheric science. New York: John Wiley & Sons, 2003, 137–163, 2003.

11 - Neal JC, Atkinson PM, Hutton CW. Flood Inundation model updating using ensemble Kalman filter and spatially distributed measurements. Journal of Hydrology. 2007. 336: 401-415.

12 - Block PJ, Francisco ASF, Liqiang S, Hyun-Han K. A Streamflow Forecasting Framework Using Multiple Climate and Hydrological Models. Journal of the American Water Resources Association (JAWRA). 2009, 45(4), 828-843. DOI: 10.1111 ⁄ j.1752-1688.2009.00327.x

13 - Rajagopalan B, Lall U, Zebiak SE. Categorical Climate Forecasts Through Regularization and Optimal Combination of Multiple GCM Ensembles. Monthly Weather Review, 2002, 130:1792-1811.

14 - Duan Q, Ajami NK, Gao X, Sorooshian S. Multi-Model Ensemble Hydrologic Prediction Using Bayesian Model Averaging. Advances in Water Resources, 2006, 30, 1371-1386.

15 - Bourdin DR, Nipen TN, Stull RB. Reliable probabilistic forecasts from an ensemble reservoir inflow forecasting system. Water Resources Research, 2014, 50, 3108–3130. doi:10.1002/2014WR015462.

16 - Krzysztofowicz, R. The case for probabilistic forecasting in hydrology. Journal of Hydrology, 2001, 249(1–4), 2–9, doi:10.1016/S0022–1694(01)00420-6.

17 - Xie X, Zhang D. Data assimilation for distributed hydrological catchment modeling via ensemble Kalman filter. Advances in Water Resources. 2010, 33, 678–690. doi:10.1016/j.advwatres.2010.03.012.

18 - Jeong J, Kannan N, Arnold J, Glick R, Gosselink L, Srinivasan R. Development and Integration of Sub-hourly Rainfall–Runoff Modeling Capability Within a Watershed Model. Water Resour Manage. 2010; 24, 4505–4527. doi: 10.1007/s11269-010-9670-4

19 - Arnold JG, Srinivasan R, Muttiah RS, Williams JR. Large-area hydrologic modeling and assessment: Part I. Model development. Journal of the American Water Resources Association. 1998; 34(1), 73-89.

20 - Bressiani DA, Gassman PW, Fernandes JG, Garbossa LHP, Srinivasan R, Mendiondo EM, Bonumá NB. 2015. A review of SWAT (Soil and Water Assessment Tool) applications in Brazil: challenges and prospects. International Journal of Agricultural and Biological Engineering (IJABE). 2015, 8(3), 9-35. DOI: 10.3965/j.ijabe.20150803.1765.

21 - Gassman PW, Reyes MR, Green CH, Arnold JG, The soil and water assessment tool: Historical development, applications, and future research directions. Transactions ASAE. 2007, 50(4), 1211–1250.

22 - Williams JR, Arnold JG, Kiniry JR, Gassman PW, Green CH. History of model development at Temple, Texas. Hydrol. Sci. 2008; 53(5), 948-960.

23 - King KW, Arnold JG, Bingner RL. Comparison of Green-Ampt and curve number methods on Goodwin Creek Watershed using SWAT. Transactions of the ASAE. 1999; 42(4): 919-925.

24 - Bouraoui F, Benabdallah S, Jrad A, Bidoglio G. Application of the SWAT model on the Medjerda river basin (Tunisia). Physics and Chemistry of the Earth. 2005; 30, 497–507.

25 - Van Griensven A, Bauwens W. Application and evaluation of ESWAT on the Dender basin and the Wister Lake basin. Hydrol. Process. 2005, 19, 827–838. doi: 10.1002/hyp.5614.

26 - Kannan N, White SM, Worrall F, Whelan MJ. Sensitivity analysis and identification of the best evapotranspiration and runoff options for hydrological modelling in SWAT-2000. Journal of Hydrology. 2007; 332: 456– 466. doi:10.1016/j.jhydrol.2006.08.001.

27 - Jeong J, Kannan N, Arnold JG, Glick R, Gosselink L, Srinivasan R, Harmel RD. Development of sub-daily erosion and sediment transport algorithms for SWAT. Transactions of the ASABE. 2011; 54(5): 1685-1691. ISSN 2151-0032.

28 - Maharjan GR, Park YS, Kim NW, Shin DS, Choi JW, Hyun GW, Jeon J-H, Ok YS, Lim KJ. Evaluation of SWAT sub-daily runoff estimation at small agricultural watershed in Korea. Front. Environ. Sci. Eng. 2013; 7(1): 109 – 119. doi: 10.1007/s11783-012-0418-7.

29 - Boithias L, Bressiani DA, Sauvage S, Abbaspour KC, Srinivasan R, Ludwig W, Richard E, Sanchez-Perez JM. Does the use of fine climate stations grid and sub-basins delineation improve the modelling of river discharge and sediments fluxes at hourly time-step? Application of the SWAT model to Mediterranean flash floods. 2015. 2015 SWAT Conference, Book of Abstracts.

30 - Neitsch SL, Arnold JG, Kiniry JR, Williams JR. Soil and Water Assessment Tool Theoretical Documentation Version 2009. 2011. Texas Water Resources Institute Technical Report No. 406. Texas A&M University System, College Station, Texas 77843-2118.

31 - Bressiani DA, Srinivasan R, Sauvage S, Sanchez Perez JM, Mendiondo EM. Systematic Procedure for Calibrating Complex Watersheds: Case Study Application in Southeast Brazil. Agricultural Water Management, 2016. “In review” (Chapter 4).

32 - Burrough PA, McDonnell RA. Creating continuous surfaces from point data, in: Burrough, PA, Goodchild, MF, McDonnell, RA, Switzer, P, Worboys M. (Eds.), Principles of Geographic Information Systems, 1998. Oxford University Press, Oxford, UK, 333pp.

33 - Zhang X, Srinivasan R. GIS-Based Spatial Precipitation Estimation: A Comparison of Geostatistical Approaches. Journal of the American Water Resources Association (JAWRA), 2009, 45(4), 894-906. doi:10.1111/j.1752-1688.2009.00335.x

34 - Abbaspour KC, 2011. SWAT-CUP4: SWAT Calibration and Uncertainty Programs - A User Manual. © Eawag 2011. Available: http://www.eawag.ch/forschung/siam/software/swat/index_EN. Accessed on: 2013-05-13.

35 - Abbaspour KC, Yang J, Maximov I, Siber R, Bogner K, Mieleitner J, Zobrist J, Srinivasan R, Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. Journal of Hydrology, 2007, 333, 413-430.

36 - Abbaspour KC, Rouholahnejad E, Vaghefi S, Srinivasan R, Yang H, Kløve B. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. Journal of Hydrology, 2015. 524, 733-752. doi:10.1016/j.jhydrol.2015.03.027

37 - Muleta MK, Nicklow JW. Sensitivity and uncertainty analysis coupled with automatic calibration for a distributed watershed model. Journal of Hydrology; 2004, 306(1–4), 127–145.

38 - van Griensven A, Meixner T, Grunwald S, Bishop T, Diluzio M, Srinivasan R. A global sensitivity analysis tool for the parameters of multi-variable catchment models. 2006. Journal of Hydrology, 324, 10–23. doi:10.1016/j.jhydrol.2005.09.008.

39 - Arnold JG, Moriasi DN, Gassman PW, Abbaspour KC, White MJ, Srinivasan R, et al. SWAT: model use, calibration, and validation. Trans. ASABE, 2012. 55(4): 1491-1508. DOI: 10.13031/2013.42256.

40 - Nash JE, Sutcliffe JV. River flow forecasting through conceptual models: Part 1. A discussion of principles. J. Hydrology, 1970, 10(3), 282-290.

41 - Gupta HV, Sorooshian S, Yapo PO. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. J. Hydrologic Eng. 1999. 4(2), 135-143.

42 - Abbaspour KC, Johnson CA, van Genuchten MTh. Estimating Uncertain Flow and Transport Parameters Using a Sequential Uncertainty Fitting Procedure. Vadose Zone Journal, 2004, 3, 1340–1352.

43 - Collischonn W, Haas R, Andreolli I, Tucci CEM. Forecasting River Uruguay flow using rainfall forecasts from a regional weather-prediction model. Journal of Hydrology. 2005; 305, 87–98. doi:10.1016/j.jhydrol.2004.08.028.

44 - Collischonn W, Tucci CEM, Clarke RT, Chou SC, Guilhon LG, Cataldi M, Allasia D. Medium-range reservoir inflow predictions based on quantitative precipitation forecasts. Journal of Hydrology. 2007; 344, 112– 122. doi:10.1016/j.jhydrol.2007.06.025.

45 - Bravo JM, Paz AR, Collischonn W, Uvo CB, Pedrollo OC, Chou SC. Incorporating Forecasts of Rainfall in Two Hydrologic Models Used for Medium-Range Streamflow Forecasting. J. Hydrol. Eng. 2009, 14(5): 435-445. DOI: 10.1061/ (ASCE) HE.1943-5584.0000014

46 - Paiva RCD, Collischonn W, Bonnet M-P, de Gonçalves LGG, Calmant S, Getirana A, Santos da Silva J. Assimilating in situ and radar altimetry data into a large-scale hydrologic-hydrodynamic model for streamflow forecast in the Amazon. Hydrol. Earth Syst. Sci. 2013. 17, 2929–2946. doi:10.5194/hess-17-2929-2013.

47 - Fan FM, Collischonn W, Meller A, Botelho LCM. Ensemble streamflow forecasting experiments in a tropical basin: The São Francisco river case study. Journal of Hydrology. 2014; 519: 2906–2919. http://dx.doi.org/10.1016/j.jhydrol.2014.04.038.

48 - Fan FM, Collischonn W, Quiroz KJ, Sorribas MV, Buarque DC, Siqueira VA. Flood forecasting on the Tocantins River using ensemble rainfall forecasts and real-time satellite rainfall estimates. J Flood Risk Management. 2015. DOI: 10.1111/jfr3.12177.

49 - Fan FM, Schwanenberg D, Collischonn W, Weerts A. Verification of inflow into hydropower reservoirs using ensemble forecasts of the TIGGE database for large scale basins in Brazil. Journal of Hydrology: Regional Studies. 2015; 4: 196–227. http://dx.doi.org/10.1016/j.ejrh.2015.05.012.

50 - Fernandez Bou AS, Ventura De Sá R, Cataldi M. Flood forecasting in the upper Uruguay River basin. Nat Hazards. 2015; 79:1239–1256. DOI 10.1007/s11069-015-1903-7.

51 - Mesinger F, Janjic ZI, Ničkovic S, Gavrilov D, Deaven DG. The step-mountain coordinate: Model description and perfor-mance for cases of Alpine Lee cyclogenesis and for a case of Appala-chian redevelopment. Mon. Weather Rev., 1988. 116(7), 1493 – 1518.

52 – Mesinger F; Chou, SC; Gomes JL;Jovic D; Bustamante J F; Lyra AA; Bastos, Paulo; Veljovic, K;Lazic, Lazar; Morelli S; Ristic I . An upgraded version of the Eta model. Meteorology and Atmospheric Physics 2012, 116, 63-79.

53 - Chou SC; Nunes AMB and Cavalcanti IFA. Extended range forecasts over South America using the regional Eta model. Journal of Geophysical Research, Estados Unidos, 2000, 105(8), 10147-10160,

54 - Seluchi ME; Chou SC. Synoptic patterns associated with landslide events in the Serra do Mar, Brazil. Theoretical and Applied Climatology, 2009

55 - Dereczynski CP, Pristo MVJ, Chou SC, Cavalcanti IFA, Rozante JR. Avaliaçao das previsões do Modelo Eta na regiao da Serra do Mar (Estado de Sao Paulo), Brasil. Anuário do Instituto de Geociências/UFRJ . 2010

56 - Chou SC, Kruk NS, Vendrame I. Coupling a Mesoscale Atmospheric Model with a Distributed Hydrological Model Applied to a Watershed in Southeast Brazil. Journal of Hydrologic Engineering. 2013, 18(1), 58-65, 10.1061/(ASCE)HE.1943-5584.0000606.

57 - Seluchi ME, Chou SC, Gramani M. A case study of winter heavy rainfall event over the Serra do Mar in Brazil. Geofísica Internacional. 2011, 50(1), 41-56.

58 - Betts, AK, Miller MJ. A new convective adjustment scheme. Part II: Single column tests using GATE wave, BOMEX, ATEX, and Arctic Airmass data sets. Quarterly Journal of the Royal Meteorological Society, 1986, 112, 693 -710.

59 - Janjic ZI. The step-mountain eta coordinate model: Further de-velopments of the convection, viscous sublayer, and turbulence closure schemes, Monthly Weather Review, 1994, 122(5), 927 – 945.

60 Kain JS. The Kain Fritsch Convective Parameterization : An update, Journal of Applied Meteorology, 2004, 20(1),170-181 -http://journals.ametsoc.org/doi/abs/10.1175/1520-0450(2004)043%3C0170% 3ATKCPAU%3E2.0.CO%3B2

61 - Ferrier BS, Jin Y, Lin Y, Black T, Rogers E, DiMego G. Implementation of a new grid-scale cloud and precipitation scheme in the NCEP Eta Model. 19th Conf. on Weather Analysis and Forecasting/15th Conf. on Numerical Weather Prediction, American Meteorological Society, 2002, San Antonio, 280.

62 - The Grid Analysis and Display System GrADS V1.5.1.12 Brian Doty doty@cola.iges.org 10 September, 1995; Manual reformatted and updated by: Tom Holt, Climatic Research Unit, University of East Anglia, Norwich, UK. t.holt@uea.ac.uk and Mike Fiorino Program for Climate Model Diagnosis and Intercomparison Lawrence Livermore National Laboratory L-264 Livermore, CA 94551 fiorino@typhoon.llnl.gov

63 - Tarantola A. Inverse problem theory and methods for model parameter estimation,. 1156 Philadelphia, PA: Society for Industrial Mathematics, 2005

64 - McLaughlin, DM, An integrated approach to hydrologic data assimilation: interpolation, smoothing, and filtering. Advances in Water Resources, 2002, 25, 1275-1286.

65 - Babovic V, Fuhrman DR. Data assimilation of local model error forecasts in a deterministic model, International Journal for Numerical Methods in Fluids, 2002, 39(10), 887-918

66 - Neal JC, Atkinson PM, Hutton CW. Flood inundation model updating using an ensemble Kalman filter and spatially distributed measurements. Journal of Hydrology, 2007, 336, 401-415.

67 - Vrugt JA, Diks CGH, Gupta HV, Bouten W, Verstraten JM, Improved treatment of uncertainty in hydrologic modeling: Combining the strengths of global optimization and data assimilation. Water Resources Research, 2005, 41, W01017, doi:10.1029/2004WR003059.

68 - Moriasi D, Arnold JG, Van Liew MW, Bingner R, Harmel R, Veith TL. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE, 2007. 50: 885-900. doi: http://ddr.nal.usda.gov/handle/10113/9298.

69 - Neal JC, Atkinson PM, Hutton CW. Flood inundation model updating using an ensemble Kalman filter and spatially distributed measurements. Journal of Hydrology, 2007, 336, 401-415.

70 - The Grid Analysis and Display System GrADS V1.5.1.12 Brian Doty doty@cola.iges.org 10 September, 1995

71 - Manual reformatted and updated by: Tom Holt, Climatic Research Unit, University of East Anglia, Norwich, UK. t.holt@uea.ac.uk and Mike Fiorino Program for Climate Model Diagnosis and Intercomparison Lawrence Livermore National Laboratory L-264 Livermore, CA 94551 fiorino@typhoon.llnl.gov

7. *General Conclusions*

Overall we believe the methodologies and results for the Piracicaba watershed are sound. And that they can be replicated in other watersheds in Brazil and around the world. The proposed mapping assessments of flooding vulnerability and risks (chapter two) can be applied for the entire Brazil, and could be used as a tool in water resources management and planning. The watershed model (SWAT) used on this doctoral thesis also proved to be a versatile and robust model, with several good example applications around the world and in Brazil (chapter three). It proved to be good for the Piracicaba case study for the main water balance components, having in focus especially flow, for yearly averages, monthly and daily time-steps. The step by step calibration methodology, as well as the different calibrations performed can help other modelers on choosing where and how to calibrate their own models.

For hourly application, this work is pioneer, in area scale, as well as on the SWAT-CUP hourly automatic calibration. We also believe the results are good, that this is a promising field of study, and that it can be greatly improved with the increase on data availability and quality. Therefore the SWAT model was very good for our goals, as also the developed models for the Piracicaba watershed can be continuously built on, exploring more different fields (as for example water quality and crop growth, etc), and improved. Also we believe the lessons learnt in this thesis can improve and aid in several watershed models applications worldwide.

The last section with ensemble flow forecasting and data assimilation show a little of what can be performed with this kind of application. We also deem that the concepts and methodology are good and could be replicated for different case studies and used for real time applications in streamflow forecasting. As also this can be greatly developed as it is a promising field of research. Overall the chapters of this thesis incorporate a number of different concepts, meteorological frameworks, ideas and applications to contribute to water resources management and flooding risks management; vulnerability and flooding risk mapping assessments, watershed and hydrological modeling, calibration and streamflow forecasting, for specific technical conclusions and findings please refer to the chapters conclusions in each chapter.

8. *Publications and other relevant activities conducted on the period*

Papers published in peer-review journals

1. Bressiani DA; Gassman PW; Fernandes JG; Garbossa LHP; Srinivasan R; Bonuma NB; Mendiondo EM. Review of Soil and Water Assessment Tool (SWAT) applications in Brazil: Challenges and prospects. International Journal of Agricultural and Biological Engineering, 2015, 8, 9-35.

2. Bressiani DA; Srinivasan R; Jones CA; Mendiondo EM. Effects of spatial and temporal weather data resolutions on streamflow modeling of a semi-arid basin, Northeast Brazil. International Journal of Agricultural and Biological Engineering, 2015, 8, 125-139.

Papers published in conference proceedings

1. Ribeiro CBM; Bressiani DA; Rottunno Fo. OCR. Modelagem hidrológica de vazões na bacia amazônica utilizando o modelo SWAT. In: XXI Simpósio Brasileiro de Recursos Hídricos, 2015, Brasília. Anais do XXI Simpósio Brasileiro de Recursos Hídricos. Porto Alegre, RS: ABRH/Acquacon, 2015. v. XXI.
2. Fava MC; Santana G; Bressiani DA; Rosa A; Horita FEA; Souza VCB; Mendiondo EM . Integration of information technology systems for flood forecasting with hybrid data sources. In: 6th International Conference on Flood Management, 2014, São Paulo. Proceeding of the 6th international conference on flood management - ICFM6, 2014.
3. Silva CR; Bressiani DA; Bettiol GM; Crestana S. Aplicação do modelo SWAT (Soil and Water Assessment Tool) para estimar produção de sedimento e nutrientes na microbacia experimental da EMBRAPA pecuária SUDESTE. In: Simpósio Nacional de Instrumentação Agropecuária, 2014, São Carlos-SP. Anais do Simpósio Nacional de Instrumentação Agropecuária, 2014.
4. Mendiondo EM; Pimentel I; Bressiani DA; Rodrigues DB. Demandas atuais e futuras sob incertezas e adaptações de longo prazo em bacias do Jaguaribe e Piranhas-Açu. In: XX Simp. Bras. Rec. Hídricos, 2013, Bento Gonçalves. Água: Desenvolvimento Econômico e Sócio-Ambiental. Porto Alegre, RS: ABRH/Acquacon, 2013, 1,561-570.
5. Bressiani DA; Laurentis G; Mendiondo EM. Estratégias de adaptação à mudança climática e de gestão de risco de desastres ambientais; horizontes de previsão de curto e longo prazos. In: Congresso Brasileiro Sobre Desastres Naturais, 2012, Rio Claro. Anais do Congresso Brasileiro Sobre Desastres Naturais, 2012, 2012.
6. Bressiani DA; Bertazi MH; Brandao JLB; Mendiondo EM. Análise hidrológica de duas sub-bacias urbanas - São Carlos, SP. In: XI Simpósio De Recursos Hídricos do Nordeste, 2012, João Pessoa. Anais do XI Simpósio De Recursos Hídricos do Nordeste, 2012.
7. Leyh W; Gutierrez LAR; Bressiani DA; Mendiondo EM; Albuquerque JP. SDI - GEO Web Services for research, administration and sharing of environmental data and information of different climate change scenarios at peri-urban river basin scales. In: 5th International

Seminar on Environmental Planning and Management Urban Responses for Climate Change, 2012, Brasília. Proceedings 5th International Seminar on Environmental Planning and Management Urban Responses for Climate Change. Brasília, 2012.

8. Laurentis G; Pimentel I; Bressiani DA; Mendiondo EM. Aplicabilidade de modelos de transferência de riscos hidrológicos como estratégia da adaptação a eventos extremos.. In: XIX Simpósio Brasileiro de Recursos Hídricos, 2011, Maceió, AL. Anais do XIX Simpósio Brasileiro de Recursos Hídricos, 2011.
9. Rodrigues D; Bressiani DA; Oliveira P; Mendiondo EM. Incentivos para conservação do solo e dos recursos hídricos a partir da pegada hídrica (water footprint). In: XIX Simpósio Brasileiro de Recursos Hídricos, 2011, Maceió, AL. Anais do XIX Simpósio Brasileiro de Recursos Hídricos, 2011.
10. Zaffani A; Bressiani DA; Pehovaz-Alvarez R; Mendiondo EM. A poluição da drenagem urbana relacionada com a pegada hídrica cinza: caso da cidade de São Carlos, SP. In: XIX Simpósio Brasileiro de Recursos Hídricos, 2011, Maceió, AL. Anais do XIX Simpósio Brasileiro de Recursos Hídricos, 2011.
11. Bressiani DA; Hecht J; Cheng L; Abdou S; Thomas A; Newburn D; Cai X; Mendiondo, EM. Aplicação de modelos SWAT, WEAP, e GAMS para otimização econômica de demandas agrícolas sujeitas a restrições ambientais. In: XIX Simpósio Brasileiro de Recursos Hídricos, 2011, Maceió-AL. Anais do XIX Simpósio Brasileiro de Recursos Hídricos, 2011. p. 1-20.

Expanded abstracts published in conference proceedings

1. Fini PH; Colombo A; Bressiani DA; Ueyama J. Integrando o sensor de poluição no Projeto e-Noé. In: VI Workshop de Iniciação Científica e Tecnológica, 2012, São Carlos. Anais do VI Workshop de Iniciação Científica e Tecnológica, 2012.
2. Colombo A; Fini PH; Bressiani DA; Ueyama J. Construindo o sensor de poluição para rios urbanos no Projeto e-Noé. In: 1º Simpósio de Iniciação Científica em Engenharia Elétrica de São Carlos, 2012, São Carlos. Anais do 1º Simpósio de Iniciação Científica em Engenharia Elétrica de São Carlos, 2012.
3. Shiratsubaki I; Bressiani DA; Kawatoko I; Mendiondo EM. Novas Tecnologias e Inovação com Pegada Hídrica e Medidas Compensatórias de Águas Urbanas em Escala Domiciliar. In: SIICUSP, Simpósio Internacional de Iniciação Científica, 2011, São Paulo. Anais do Simpósio Internacional de Iniciação Científica (SIICUSP), 2011.

Abstracts published in conference proceedings

1. Molin PG; Bressiani DA; Cassiano CC; Ferraz SFB. Natural forest scenarios and hydrological responses in an agricultural watershed in Brazil. In: 4th International Conference on Forests and Water in a Changing Environment, 2015, Kelowna. 4 th IUFRO International Conference on Forests and Water in a Changing Environment. Kelowna: University of British Columbia Okanagan, 2015. v. 4. p. 1-223.
2. Boithias L; Bressiani DA; Sauvage S; Abbaspour KC; Srinivasan R; Ludwig W; Richard E; Sanchez-Perez JM. Does the use of fine climate stations grid and sub-basins delineation

improve the modelling of river discharge and sediments fluxes at hourly time-step? Application of the SWAT model to Mediterranean flash floods. In: 2015 International SWAT Conference, 2015, Pula, Sardinia. 2015 International Soil & Water Assessment Tool Conference, 2015. p. 1-209.

3. Ribeiro CBM; Bressiani DA; Rottunno Fo. OCR; Srinivasan R. Effects of Global and Measured Weather Datasets on Amazon Basin Streamflow SWAT simulation. In: 2015 SWAT International Conference, 2015, Pula, Sardinia. 2015 Soil & Water Assessment Tool International Conference, 2015.
4. Bressiani DA; Srinivasan R; Mendiondo EM; Abbaspour KC. SWAT Hourly Calibration using SWAT-CUP for a Large Watershed in Southeast Brazil and Flooding Applications. In: http://swat.tamu.edu/media/114704/swat-italy-2015-book-of-abstracts-2015-06-10.pdf, 2015, Pula, Sardinia. 2015 Soil & Water Assessment Tool International Conference, 2015.
5. Bressiani DA; Srinivasan R; Mendiondo EM. Searching for better model performance and reduced optimization time: different calibration methods on different watershed locations. In: 2014 International SWAT Conference, 2014, Ipojuca, PE, Brasil. 2014 International SWAT Conference - Book of Abstracts, 2014.
6. Ribeiro CBM; Mohanty BP; Bressiani DA; Fernandes JG; Rottunno Fo. OCR. Parameterization of physical and climatic characteristics in the Amazon basin for hydrological simulation with SWAT model. In: 2014 International SWAT Conference, 2014, Ipojuca, PE, Brasil. 2014 International SWAT Conference - Book of Abstracts, 2014.
7. Taffarello D; Bressiani DA; Calijuri MC; Mendiondo EM. On contrasting field evidences of water quality to perform physically-based SWAT simulations in challenging Brazilian biome under change. In: 2014 International SWAT Conference, 2014, Ipojuca, PE, Brasil. 2014 International SWAT Conference - Book of Abstracts, 2014.
8. Oliveira LT; Bressiani DA; Cecilio RA; Mendes HA; Dambroz CS. SWAT application for Santa Maria of Vitória Watershed at Espírito Santo (ES), Brazil. In: 2014 International SWAT Conference, 2014, Ipojuca, PE, Brasil. 2014 International SWAT Conference - Book of Abstracts, 2014.
9. Molin PG; Bressiani DA; Ferraz SFB; Mendiondo EM; Srinivasan R. Effects of Atlantic Forest Patches on Water-Regulation Ecosystem Services. In: 2014 International SWAT Conference, 2014, Ipojuca, PE, Brasil. 2014 International SWAT Conference - Book of Abstracts, 2014.
10. Bressiani DA; Srinivasan R; Jones CA; Mendiondo EM. Climate change impacts on the streamflow of a semi-arid watershed, Northeast Brazil. In: 2014 International SWAT Conference, 2014, Ipojuca, PE, Brasil. 2014 International SWAT Conference - Book of Abstracts, 2014.
11. Bressiani DA; Srinivasan R; Jones CA; Rodrigues D; Pimentel I; Mendiondo EM. Effects of different spatial and temporal weather data resolutions on streamflow modeling of a semi-arid basin, Northeast Brazil. In: 2013 International SWAT Conference, 2013, Toulouse, France. 2013 International SWAT Conference - Book of Abstracts, 2013.
12. Fernandes JG.; Bressiani DA; Villas Boas M; Srinivasan R; Ganvincio JD; Freire MGS. SWAT applications in Brazil: A Survey of the Past 10 years. In: 2013 International SWAT

Conference, 2013, Toulouse, France. 2013 International SWAT Conference - Book of Abstracts, 2013.

Awards

1. Award of Best Oral Presentation on the 2014 International SWAT Conference, Texas A&M University, ARS-USDA, UFPE, UFRPE.Bressiani DA; Srinivasan R; Mendiondo EM. Searching for better model performance and reduced optimization time: different calibration methods on different watershed locations. In: 2014 International SWAT Conference, 2014, Ipojuca, PE, Brasil. 2014 International SWAT Conference - Book of Abstracts, 2014.
2. Second best presentation on VI Workshop de Iniciação Científica e Tecnologia, 15ª Semana da Computação do ICMC/USP., ICMC/USP. Fini PH; Colombo A; Bressiani DA; Ueyama J. Integrando o sensor de poluição no Projeto e-Noé. In: VI Workshop de Iniciação Científica e Tecnológica, 2012, São Carlos. Anais do VI Workshop de Iniciação Científica e Tecnológica, 2012.

Presentations/Lectures in other events

1. Bressiani DA. Soil & Water Assessment Tools (SWAT); o modelo, aplicações no Brasil, e estudos de caso. 2014.(Seminário Técnico - Embrapa Meio Ambiente, Jaguariuna, SP.
2. Bressiani DA; Mendiondo EM . Proposal of a Decision Support System with short and long-term adaptation strategies for flood resilient cities.. 2012. IPCC SREX-FAPESP- Regional Outreach Meeting: Managing the Risks of Climate Extremes and Disasters in Central and South America. What can we learn from the IPCC Especial Report on Extremes SREX? São Paulo, SP
3. Bressiani DA; Mendiondo EM. Web-Mapping Decision Support System for Urban Floods? Long and Short Term adaptation strategies. 2012. Interdisciplinary Doctoral Seminar on Climate Change - University Global Partership Network: North Carolina State University, University of Surrey, University of São Paulo; Raleigh-NC, Nags Head-NC, Washington-DC
4. Bressiani DA; Laurentis, G; Mendiondo EM . Legislación sobre Caudales Ecológicos en Brasil. 2011, VIAgua - Taller Caudales Ecológicos: Vulnerabilidad, Impacto y Adaptación al Cambio Climático, Universidad De La República – Udelar, Universidad De Montevideo, Uruguai
5. Bressiani DA; Mendiondo EM . Métodos hidrológicos (SWAT, WEAP y GAMS) y Estudo de Caso. 2011. VIAgua - Taller Caudales Ecológicos: Vulnerabilidad, Impacto y Adaptación al Cambio Climático Universidad De La República – Udelar, Universidad De Montevideo, Uruguai
6. Bressiani DA; Rodrigues D; Pimentel I; Mendiondo EM. Riscos de escassez hídrca no Brasil e no Mundo: Pegada hídrica como instrumento de adaptação. 2011. Seminário de Meio Ambiente BRASKEM, Camaçari, BA
7. Bressiani DA; Mendiondo EM. Sistemas de alerta hidrologico para disminucion de vulnerabilidad y prevencion de desastres en áreas urbanas de Brasil: nuevos desafios para la adaptacion de ciudades resilientes. 2011. Jornadas PROHIMET México 2011 - Operación de

las redes hidrometeorológicas para la prevención de desastres, PROHIMET, Querétaro, México

8. Mendiondo EM; Bressiani DA; Pimentel I; Rodrigues D. Metodologias para cálculo de demanda hídrica. 2011. Workshop do Banco Mundial: Metodologia para a análise do clima, hidrologia e demanda de água nas bacias do Jaguaribe e Piranhas- Açu, FUNCEME, Fortaleza, CE
9. Mendiondo EM; Pimentel I; Bressiani DA ; Rodrigues D. Demanda hídrica - apresentação de resultados. 2011 Workshop Banco Mundial: Disponibilidade de Água e Demanda Presente e Futura. Desafios Detectados na Alocação de Água nas Bacias do Jaguaribe e Piranhas-Açu no contexto de Mudanças Climáticas, João Pessoa PB
10. Mendiondo EM ; Pimentel I ; Rodrigues D. ; Bressiani DA. Demanda - apresentação de dados e metodologia. 2011. Workshop do Banco Mundial: Apresentação de Resultados Parciais na Análise do Clima, Hidrologia e Demanda de Água nas Bacias do Jaguaribe e Piranhas-Açu, e Discussão Metodológica sobre Ferramentas de Alocação no contexto de Mudanças Climáticas, Natal, RN
11. Bressiani DA; Srinivasan R; Jones CA; Mendiondo EM. Modelagem Hidrológica com SWAT para a Bacia do Jaguaribe. 2011. Workshop do Banco Mundial: Apresentação de Resultados Parciais na Análise do Clima, Hidrologia e Demanda de Água nas Bacias do Jaguaribe e Piranhas-Açu, e Discussão Metodológica sobre Ferramentas de Alocação no contexto de Mudanças Climáticas, Natal, RN

Development of instructional material

1. Bressiani DA; Srinivasan R; Jones CA. Tutorial básico do modelo hidrológico Soil and Water Assessment Tool (SWAT) https://www.youtube.com /watch?v=jDRmf7zGjVo em português. 2011. (vídeo).
2. Bressiani DA; Srinivasan R; Apostila Tutorial do Modelo ArcSWAT em português. 2014.

Short courses given

1. Bressiani DA- Curso Avançado de Modelagem Hidrológica (Calibração do SWAT). 24 horas de duração. Em 7 Workshop de Mudanças Climáticas e Recursos Hídricos do Estado de Pernambuco e 4 Workshop Internacional Sobre Mudanças Climáticas e Biodiversidade. UFPE e ITEP. Recife, 2015.
2. Bressiani DA. Workshop Introdutório do Modelo SWAT. 16 horas de duração 2014 International SWAT Conference, Texas A&M University, Universidade Federal de Pernambuco (UFPE), Universidade Federal Rural de Pernambuco (UFRPE), Universidade de São Paulo (USP), Recife, PE, 2014
3. Srinivasan R; Bressiani DA; Jones CA. Curso Introdutório e Avançado sobre modelagem com o modelo SWAT (Soil & Water Assessment Tool). 36 horas de duração, Escola de Engenharia de Sao Carlos-USP, S.Carlos, SP, 2012.

4. Bressiani DA; Srinivasan R; Vazquez V; Jones CA. Curso Introdutório sobre modelagem de oferta hídrica com o modelo SWAT (Soil & Water Assessment Tool). Banco Mundial, Natal, RN, 2011.

Organization of events and conferences

1. Bressiani DA; Mendiondo EM; Srinivasan R. Workshop QSWAT Brasil: Aplicações em Sistemas de Alertas de Desastres Naturais com Tecnologicas de Baixo Custo. 2015.
2. Bressiani DA; Fernandes JG; Montenegro SMGL; Srinivasan R. 2014 International SWAT Conference. Porto de Galinhas, PE. 2014. (Congresso).
3. Bressiani DA; Fernandes JG; Srinivasan R. SWAT Introductory and Advanced Workshops. Recife – PE. 2014.
4. Bressiani DA; Pimentel I; Mendiondo EM; Ambrizzi, T. Curso sobre o Modelo SWAT - INCLINE – USP, São Paulo. 2012.
5. Bressiani DA; Garbossa L; Srinivasan R; Jones CA; Mendiondo EM. Curso Introdutório e Avançado sobre modelagem com o modelo SWAT (Soil & Water Assessment Tool), Florianópolis e São Carlos. 2012.

Reviewer of the following journals

- Revista Brasileira de Geografia Física
- Hydrology and Earth System Sciences Discussions (Online)
- Catena (Cremlingen)
- Revista Brasileira de Recursos Hídricos
- Climatic Change