UNIVERSIDADE FEDERAL RURAL DE PERNAMBUCO

DEPARTAMENTO DE ENGENHARIA AGRÍCOLA

CAROLYNE WANESSA LINS DE ANDRADE

Hydrological modeling and scenarios of land use and climate changes in a representative basin, northeastern Brazil

Recife

2018

CAROLYNE WANESSA LINS DE ANDRADE

Hydrological modeling and scenarios of land use and climate changes in a representative basin, northeastern Brazil

Doctoral thesis presented at Universidade Federal Rural de Pernambuco (Federal Rural University of Pernambuco) in partial fulfillment of the requirements for obtaining the Degree of Doctor in Science: Agricultural Engineering.

Advisor: Prof^{a}. Dra. Suzana Maria Gico Lima Montenegro

Co-Advisors: Prof. Dr. Abelardo Antônio de Assunção Montenegro

Prof. Dr. José Romualdo de Sousa Lima

Recife

2018

Dados Internacionais de Catalogação na Publicação (CIP)
Sistema Integrado de Bibliotecas da UFRPE
Biblioteca Centra, Recife-PE, Brasil

A553h Andrade, Carolyne Wanessa Lins de
Hydrological modeling and scenarios of land use and climate changes in a representative basin, northeastern Brazil / Carolyne Wanessa Lins de Andrade. – 2018.
161 f. : il.

Orientadora: Suzana Maria Gico Lima Montenegro.
Coorientadores: Abelardo Antônio de Assunção Montenegro e José Romualdo de Sousa Lima.
Tese (Doutorado) – Universidade Federal Rural de Pernambuco, Programa de Pós-Graduação em Engenharia Agrícola, Recife, BR-PE, 2018.
Inclui referências e anexo(s).

1. Water resources 2. Hydrological modeling 3. Water balance 4. SWAT model 5. Soil moisture 6. Uncertainty analysis 7. Calibration 8. Validation 9. Land use 10. CMIP5 11. RCM 12. Eta-MIROC5 13. Bias correction 14. Mundaú River Watershed I. Montenegro, Suzana Maria Gico Lima, orient. II. Montenegro, Abelardo Antônio de Assunção, coorient. III. Lima, José Romualdo de Sousa, coorient. IV. Título

CDD 631

CAROLYNE WANESSA LINS DE ANDRADE

Tese apresentada em 25 de julho de 2018 ao Programa de Pós-Graduação em Engenharia Agrícola da Universidade Federal Rural de Pernambuco como parte das exigências para a obtenção do título de Doutor.

Hydrological modeling and scenarios of land use and climate changes in a representative basin, northeastern Brazil

COMISSÃO JULGADORA

Orientador: Suzana

Profª. Drª. Suzana Maria Gico Lima Montenegro
Universidade Federal de Pernambuco – UFPE

Examinadores:

Prof. Dr. Abelardo Antônio de Assunção Montenegro
Universidade Federal Rural de Pernambuco – UFRPE

Prof. Dr. Eduardo Mario Mendiondo
Escola de Engenharia de São Carlos – EESC/ USP

Josiclêda Domiciano Galvíncio

Profª. Drª. Josiclêda Domiciano Galvíncio
Universidade Federal de Pernambuco – UFPE

R. srinivasan

Prof. Dr. Raghavan Srinivasan
Texas A&M University – TAMU

Dedico este trabalho aos meus queridos pais Marvana Alves Lins de Andrade e Rinaldo José Lins de Andrade. Tudo o que sou hoje é por causa de vocês.

Agradecimentos

Gratidão! Esta palavra define o meu sentimento ao chegar à conclusão deste Doutorado. Agradeço primeiramente a Deus, por me permitir viver com saúde e perseverança para lutar pelos meus sonhos, sem Ele nada somos. Aos meus queridos pais, Marvana Alves Lins de Andrade e Rinaldo José Lins de Andrade, pelo amor incondicional. Por me ensinarem, desde cedo, a importância dos estudos, por não medirem esforços para me proporcionar uma educação de qualidade, por acreditarem nos meus sonhos e sonhá-los junto comigo. Ao meu marido, Raphael Farias Gomes da Silva, que esteve junto a mim desde o início da graduação até o presente momento. Estaremos juntos sempre.

À minha orientadora, Suzana Maria Gico Lima Montenegro, pela confiança, pelos incentivos e oportunidades, por ser uma inspiração. Aos meus co-orientadores, Abelardo Antônio de Assunção Montenegro e José Romualdo de Sousa Lima, e ao meu supervisor Raghavan Srinivasan, em especial ao professor Abelardo, pela dedicação, pelos incentivos e ensinamentos, e por também ser uma fonte de inspiração profissional.

À Universidade Federal Rural de Pernambuco (UFRPE), ao Programa de Pós-Graduação em Engenharia Agrícola (PGEA/ UFRPE), à Universidade Federal de Pernambuco (UFPE), ao Programa de Pós-Graduação em Desenvolvimento e Meio Ambiente (PRODEMA/ UFPE), à Texas A&M University (TAMU), ao Instituto de Tecnologia de Pernambuco (ITEP) e ao Departamento de Energia Nuclear (DEN/ UFPE), por todo o apoio e estrutura oferecidos. A todos os professores, alunos e funcionários destas instituições.

A toda a equipe do Laboratório de Água e Solo (LAS/ UFRPE), em especial aos bons amigos: Adriana Guedes, Adriano Monteiro, Cleene Lima, Fred Assis, José Roberto, Liliane Pinheiro, Robertson Fontes, Sonny Mateus, Thayná Almeida e Valdemir Júnior. Obrigada por todos os momentos de estudos, reuniões, além de todas as comemorações e momentos de descontração. Aos meus amigos do Programa de Pós-Graduação em Engenharia Agrícola, Ana Karina e Diego Huggins por todos os bons momentos vividos.

À Fundação de Amparo à Pesquisa do Estado de Pernambuco – FACEPE (Processos IBPG-0231-5.03/14 e BCT-0176-5.03/14; Consórcio Universitas – APQ-0300-5.03/17), à Agência Pernambucana de Águas e Clima (APAC), à Coordenação de Aperfeiçoamento de Nível Superior – CAPES (PVE aupex 2792/2013 Processo 23038007733/2013-76), ao Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq (Processo 446254/2015-0 (Projeto Super) – Chamada MCTI/CNPq/ANA Nº 23/2015; Processo 441305/2017-2 (Projeto Pegasus) – Chamada MCTI/CNPq Nº 19/2017 e Processo 307641/2013-9 (Produtividade em Pesquisa)) e à FINEP (REHIDRO 1830), pelos apoios financeiro e institucional.

À Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), ao Instituto Nacional de Meteorologia (INMET), à Agência Nacional de Águas (ANA), à Secretaria de Estado do Meio Ambiente e dos Recursos Hídricos do Estado de Alagoas (SEMARH), ao Instituto Nacional de Pesquisas Espaciais (INPE) e à Unidade Acadêmica de Garanhuns (UAG/ UFRPE), pelos dados cedidos que possibilitaram esta pesquisa.

Finalmente, a todas as pessoas e instituições que contribuíram, direta ou indiretamente, para a realização desta pesquisa. Sem o apoio de vocês, nada disso seria possível.

Muito obrigada!

Abstract

Andrade, C.W.L., 2018. Hydrological modeling and scenarios of land use and climate changes in a representative basin, northeastern Brazil. Doctoral Thesis, Federal Rural University of Pernambuco, Recife, PE, Brazil.

Water is a fundamental resource for life. The occurrence of extreme events has increased in recent decades. Understanding the effects of these events is extremely important for prevention and mitigation actions to be taken. This doctoral thesis addresses with issues related to water resources management and the impacts of land use and climate changes on the hydrological regime of the Mundaú River Basin (4,090.39 km²), northeastern Brazil. It aims to evaluate the uncertainties of the Soil and Water Assessment Tool (SWAT) calibration and validation processes and to simulate land use scenarios and future climate changes in the basin. Chapter 1 addresses the general introduction of the thesis, containing the hypothesis and general and specific objectives. Chapter 2 describes the hydro-environmental characteristics of the study area. Chapter 3 details the procedures adopted in the simulations with the SWAT model. Chapter 4 presents the evaluation of the uncertainties of the use of discharge and soil moisture data in the calibration and validation of the SWAT model in the Mundaú River Basin. Chapter 5 brings the evaluation of the effects of land use changes, based on the calibrated and validated SWAT model, on the evapotranspiration, surface runoff and sediment yield processes. Chapter 6 addresses the impacts of climate change on water resources in the basin, considering two scenarios of greenhouse gas emissions: Representative Concentration Pathways (RCPs) 4.5 and 8.5, and three time periods: short term, medium term and long term. Chapter 7 contains the general conclusions of the thesis. Finally, Chapter 8 presents a summary of the publications and other activities developed during the Doctoral research. We believe that the results found in this thesis are promising for the water management of the Mundaú River Basin, and will serve as a basis for the adoption of strategies to coexist with the scenarios of land use and climate predicted for the future. The SWAT model presented good performance and the calibration and simulation procedures adopted in this study can be replicated in other similar watersheds. The lessons learnt in this thesis may help researchers around the world to better understand the behavior of the hydrological processes of a northeastern Brazil basin under different land use and climate conditions.

Keywords: Water resources, Hydrological modeling, Water balance, SWAT model, Soil moisture, Uncertainty analysis, Calibration, Validation, Land use, CMIP5, RCM, Eta-MIROC5, Bias correction and Mundaú River Watershed.

Resumo

Andrade, C.W.L., 2018. Modelagem hidrológica e cenários de uso do solo e mudanças climáticas em uma bacia representativa do Nordeste brasileiro. Tese de Doutorado, Universidade Federal Rural de Pernambuco, Recife, PE, Brasil.

A água é um recurso fundamental para a vida. A ocorrência de eventos extremos tem aumentado nas últimas décadas. A compreensão dos efeitos causados por esses eventos é de extrema importância para que ações de prevenção e mitigação sejam tomadas. Esta pesquisa de doutorado aborda assuntos ligados à gestão dos recursos hídricos e aos impactos das modificações do uso do solo e do clima sobre o regime hidrológico da bacia hidrográfica do Rio Mundaú (4,090.39 km²), Nordeste do Brasil. Objetiva avaliar as incertezas dos processos de calibração e validação do modelo Soil and Water Assessment Tool (SWAT) e simular cenários de uso do solo e de mudanças climáticas futuras na bacia. O capítulo 1 aborda a introdução geral do trabalho, contendo a hipótese e os objetivos geral e específicos. O capítulo 2 descreve as características hidro-ambientais da área de estudo. O capítulo 3 detalha os procedimentos adotados nas simulações com o modelo SWAT. O capítulo 4 traz a avaliação das incertezas da utilização dos dados de vazão e umidade do solo na calibração e validação do modelo SWAT na Bacia do Rio Mundaú. O capítulo 5 aborda a avaliação dos efeitos das mudanças no uso do solo, a partir do modelo SWAT calibrado e validado, sobre os processos de evapotranspiração, escoamento superficial e produção de sedimentos. O capítulo 6 aborda os impactos das mudanças climáticas sobre os recursos hídricos da bacia, considerando dois cenários de emissão de gases do efeito estufa: *Representative Concentration Pathways* (RCPs) 4.5 e 8.5, e três períodos de tempo: curto prazo, médio prazo e longo prazo. O capítulo 7 contém as conclusões gerais da tese. E, por fim, o capítulo 8 apresenta um resumo das publicações e outras atividades desenvolvidas durante a pesquisa de Doutorado. Acreditamos que os resultados encontrados nesta tese são promissores para a gestão hídrica da Bacia Hidrográfica do Rio Mundaú, e servirão como base para a adoção de estratégias de convivência com os cenários de uso do solo e clima previstos para o futuro. O modelo SWAT apresentou bom desempenho e os procedimentos de calibração e simulação de cenários adotados neste estudo podem ser replicados em outras bacias hidrográficas semelhantes. As lições aprendidas nesta tese podem auxiliar pesquisadores em todo o mundo, a uma melhor compreensão do comportamento dos processos hidrológicos de uma bacia do Nordeste brasileiro sob diferentes condições de solo e clima.

Palavras-chave: Recursos hídricos, Modelagem hidrológica, Balanço hídrico, Modelo SWAT, Vazão, Umidade do solo, Análise de incertezas, Calibração, Validação, Uso do solo, CMIP5, RCM, Eta-MIROC5, Correção de tendência e Bacia Hidrográfica do Rio Mundaú.

Table of contents

List of Figures

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

List of Tables

Chapter 3

Chapter 4

Chapter 5

Chapter 6

1. General Introduction

Water is one of the fundamental resources for life. Increased human living standards, population growth and inadequate management of natural resources, among other factors, are aggravating problems related to water supply, mainly used for purposes such as irrigation, hydropower and human supply (Abbaspour et al., 2015; ONU, 2012; Silva, 2014). In regions with yearly variations of precipitation and high evaporation rates, such as some in the northeastern Brazil, these problems are even greater.

The occurrence of extreme events due to land use and climate changes, as such as droughts and floods, has increased in the last decades. According to the Intergovernmental Panel on Climate Change (IPCC) the global average surface temperature warmed by 0.85 °C from the 1880 to 2012 year, being the 21st century the warmest period (IPCC, 2013), causing changes in precipitation and considerably impacted hydrological processes. Associated to climate change, land use alterations also have occurred over the years, around the world, as such as agriculture increase, deforestation, intensive grazing and urbanization (Worku et al., 2017). Then, understanding the associated effects to land use and climate change on the water resources is extremely important for prevention and mitigation actions to be taken.

Within this context, studies focused on the understanding of hydrological processes are relevant to assist management and decision making. According to Montenegro et al. (2014) the knowledge of the different hydrological variables represents an important aspect for the adequate management of water resources. In this way, researchers from different areas have improved and implemented multiple instruments related to water resources, including the hydrological models (Bressiani et al., 2015).

Modeling is an important tool to support management and decision making on water resources. The models are able to represent the physical processes of a system, and to generate information that is not normally available, such as an overall understanding of the dynamics of the processes that occur in the soil-plant-atmosphere system. According to Abbaspour et al. (2015), hydrological models are important for the planning of water resources in meeting the diverse demands, helping in their sustainable use. The current modeling philosophy requires that the models be clearly described, and that the processes of calibration, validation, and sensitivity and uncertainty analyzes are inherent to the model.

The Soil Water Assessment Tool (SWAT), a semi-distributed, continuous-time, process based hydrology and water quality model (Neitsch et al., 2011), was developed by Dr. Jeff Arnold and his team at the Agricultural Research Service of the United States Department of Agriculture (ARS – USDA) to analyze the impacts of land use changes on discharge, erosion, sedimentation, and water quality in gauged and ungauged watersheds (Arnold et al., 1998). The SWAT is a versatile model that considers different hydrological and agronomic components and has been applied by many governmental and private institutions, as well as universities and other institutions interested in supporting decision making in the management of water resources (Bressiani et al., 2015). An extensive number of analyzes have already been carried out with SWAT worldwide, including studies on climate change (Brouziyne et al., 2018; Carvalho-Santos et al., 2017; Oliveira et al., 2017; Ouyang et al., 2015; Senent-Aparicio et al., 2017; Shiferaw et al., 2018; Sousa, 2017; Tan et al., 2017; Vaghefi et al., 2017; Zhang et al., 2016b) and land use scenarios (Anaba et al., 2017; Blainski et al., 2017; Kundu et al., 2017; Marhaento et al., 2017; Pereira et al., 2016; Worku, Khare and Tripathi, 2017; Zhang et al., 2016a).

The hypothesis of this thesis assumes that modeling is an important tool to support management and decision making on water resources. The SWAT model can efficiently simulate the hydrological processes occurring in the Mundaú River Basin, and possible discrepancies in the results obtained can be minimized by the calibration and validation procedures of the model. Additionally, it is assumed that after the calibration of the model, inferences related to the hydrological processes under different land use conditions and future climate changes in the basin can be performed based on the outputs of the simulation scenarios provided by the model.

The general objective is to analyze the uncertainties of calibration and validation of the SWAT model for the Mundaú River Basin and to simulate scenarios of land use and climate changes. The specific objectives are to evaluate the effects of uncertainties of the use of two variables on the calibration and validation of the SWAT (1), assess the issue of land use change and its effect on evapotranspiration, surface runoff and sediment yield of the study watershed (2), and to verify the impacts of the future climate change on the water resources of the basin under two representative concentration pathways (3).

References

Abbaspour, K.C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H., Klove, B., 2015. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. Journal of Hydrology, 524, 733–752. http://dx.doi.org/10.1016/j.jhydrol.2015.03.027.

Anaba, L.A., Banadda, N., Kiggundu, N., Wanyama, J., Engel, B., Moriasi, D., 2017. Application of SWAT to assess the effects of land use change in the Murchison Bay Catchment in Uganda. Computational Water, Energy, and Environmental Engineering, 6, 24-40. http://doi.org/10.4236/cweee.2017.61003.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment part I: model development. Journal of the American Water Resources Association, 34, 73-89. http://dx.doi.org/10.1111/j.1752-1688.1998.

Blainski, E., Porras, E.A.A., Garbossa, L.H.P., Pinheiro, A., 2017. Simulation of land use scenarios in the Camboriú River Basin using the SWAT model. Brazilian Journal of Water Resources, 22, 33, 1-12. http://dx.doi.org/10.1590/2318-0331.011716110.

Bressiani, D.A., Gassman, P.W., Fernandes, J.G., Garbossa, L.H.P., Srinivasan, R., Bonumá, N.B., Mendiondo, E.M., 2015. Review of Soil and Water Assessment Tool (SWAT) applications in Brazil: Challenges and prospects. International Journal of Agricultural and Biological Engineering, 8, 9-35. http://dx.doi.org/10.3965/j.ijabe.20150803.1765.

Brouziyne, Y., Abouabdillah, A., Hirich, A., Bouabid, R., Zaaboul, R., Benaabidate, L., 2018. Modeling sustainable adaptation strategies toward a climate-smart agriculture in a Mediterranean watershed under projected climate change scenarios. Agricultural Systems, 162, 154-163. https://doi.org/10.1016/j.agsy.2018.01.024.

Carvalho-Santos, C., Monteiro, A.T., Azevedo, J.C., Honrado, J.P., Nunes, J.P., 2017. Climate change impacts on water resources and reservoir management: uncertainty and adaptation for a mountain catchment in northeast Portugal. Water Resour Manage, 31, 3355–3370. https://doi.org/10.1007/s11269-017-1672-z.

Intergovernmental Panel on Climate Change. 2013. Climate change 2013: the physical science basis. Synthesis Report, Cambridge University Press, Cambridge, UK. http://www.ipcc.ch/report/ar5/wg1/ (accessed on April 2018).

Kundu, S., Khare, D., Mondal, A, 2017. Individual and combined impacts of future climate and land use changes on the water balance. Ecological Engineering, 105, 42-57. https://doi.org/10.1016/j.ecoleng.2017.04.061.

Marhaento, H., Booij, M.J., Rientjes, T.H.M., Hoekstra, A.Y., 2017. Attribution of changes in the water balance of a tropical catchment to land use change using the SWAT model. Hydrological Processes, 31, 2029-2040. http://dx.doi.org/10.1002/hyp.11167.

Montenegro, S. M. G. L., Silva, B. B., Antonino, A. C. D., Lima, J. R. S., Souza, E. S., Oliveira, L. M. M., Moura, A. E. S. S., Souza, R. M. S., 2014. Hydrological studies in experimental and representative basins in Pernambuco State, Brazil. Evolving Water Resources Systems: Understanding, Predicting and Managing Water–Society Interactions Proceedings of ICWRS2014, Bologna, Italy, June 2014 (IAHS Publ. 364, 2014).

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., Williams, J. R., 2011. Soil and Water Assessment Tool Theoretical Documentation Version 2009, Grassland, Soil and Water Research Laboratory, Agricultural Research Service and Blackland Research Center, Texas Agricultural Experiment Station, College Station, Texas, 2011.

Oliveira, V.A., Mello, C.R., Viola, M.R., 2017. Srinivasan, R. Assessment of climate change impacts on streamflow and hydropower potential in the headwater region of the Grande river basin, Southeastern Brazil. Int. J. Climatol., 37, 5005–5023. https://doi.org/10.1002/joc.5138.

ONU – United Nations Organization. Rio+20: United Nations Conference on Sustainable Development. Rio de Janeiro, Brazil 20-22 June, 2012 A/CONF.216/L.1. Available in: <http://www.uncsd2012.org/thefuturewewant.html>. Accessed in: July, 2015.

Ouyang, F., Zhu, Y., Fu, G., Lu, H., Zhang, A., Yu, Z., Chen, X., 2015. Impacts of climate change under CMIP5 RCP scenarios on streamflow in the Huangnizhuang catchment. Stoch Environ Res Risk Assess, 29, 1781–1795. https://doi.org/10.1007/s00477-014-1018-9.

Pereira, D.R., Martinez, M.A., Silva, D.D., Pruski, F.F., 2016. Hydrological simulation in a basin of typical tropical climate and soil using the SWAT Model Part II: Simulation of hydrological variables and soil use scenarios. Journal of Hydrology: Regional Studies, 5, 149–163. http://dx.doi.org/10.1016/j.ejrh.2015.11.008.

Senent-Aparicio, J., Pérez-Sánchez, J., Carrillo-García, J., Soto, J., 2017. Using SWAT and Fuzzy TOPSIS to assess the impact of climate change in the headwaters of the Segura River Basin (SE Spain). Water, 9, 149. http://dx.doi.org/10.3390/w9020149.

Shiferaw, H., Gebremedhin, A., Gebretsadkan, T., Zenebe, A., 2018. Modelling hydrological response under climate change scenarios using SWAT model: the case of Ilala watershed, Northern Ethiopia. Modeling Earth Systems and Environment, 4, 437–449. https://doi.org/10.1007/s40808-018-0439-8.

Silva, C. A. I., 2014. Análise de aplicabilidade da interface do modelo hidrológico SWAT-SIG no estudo da produção de sedimentos em uma bacia no Nordeste do Brasil. Dissertação (Mestrado em Recursos Hídricos e Saneamento) - Universidade Federal de Alagoas, Alagoas. 2014. 53p.

Sousa, R.M., 2017. Mudanças climáticas futuras simuladas pelos modelos regionais Eta-HADGEM2-ES e Eta-MIROC5 para o estado do Tocantins. Dissertation (Master in Forestry and Environmental Sciences) - Federal University of Tocantins, 96p.

Tan, M.L., Ibrahim, A.L., Yusop, Z., Chua, V.P., Chan, N.W., 2017. Atmospheric Research, 189, 1–10. http://dx.doi.org/10.1016/j.atmosres.2017.01.008.

Vaghefi, S.A., Abbaspour, N., Kamali, B., Abbaspour, K.C., 2017. A toolkit for climate change analysis and pattern recognition for extreme weather conditions e Case study: California-Baja California Peninsula. Environmental Modelling & Software, 96, 181-198. http://dx.doi.org/10.1016/j.envsoft.2017.06.033.

Worku, T., Khare, D., Tripathi, S.K., 2017. Modeling runoff–sediment response to land use/land cover changes using integrated GIS and SWAT model in the Beressa watershed. Environ Earth Sci, 76, 550, 1-14. http://dx.doi.org/10.1007/s12665-017-6883-3.

Zhang, L., Liu, Y., Wu, L., Cai, D., Ma, X., 2016a. Impact of land-use scenarios on monthly runoff modeled by SWAT. Fresenius Environmental Bulletin, 25, 9, 3595-3605.

Zhang, Y., You, Q., Chen, C., Ge, J., 2016b. Impacts of climate change on streamflows under RCP scenarios: A case study in Xin River Basin, China. Atmospheric Research, 178–179, 521–534. http://dx.doi.org/10.1016/j.atmosres.2016.04.018.

2. *Study area*

2.1 Biome and environmental conditions

The Mundaú River Basin (MRB) has a drainage area of 4,090.39 km² and is located between the geographic coordinates of 08º 42’ and 09º 36’ south latitude and, 35º 47’ and 36º 39’ longitude west (Gomes et al., 2016), spreading throughout the States of Pernambuco and Alagoas, in northeastern Brazil (Fig. 1). The MRB is limited to the north with the Una River Basin, to the south with the Alagoas State and group of basins of small rivers, to the east with the Una River Basin and Alagoas, and to the west, with the group of the interiors rivers and Una River Basin (Araújo et al., 2015).

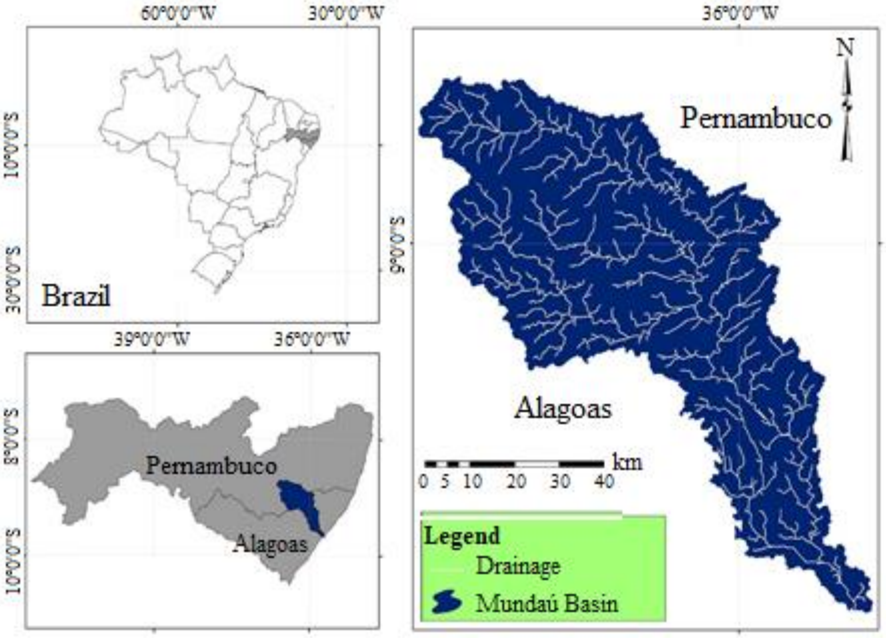


Fig. 1. Location map of Mundaú Watershed

The drainage area of the basin involves 34 municipalities, with part or all of the territory included in the basin, being 19 municipalities in the state of Alagoas and 15 municipalities in the state of Pernambuco. According to Pernambuco State Agency for Water and Climate (APAC), the municipalities Angelim, Correntes, Palmerina and São João are totally inserted in the basin. The municipalities of Brejão, Calçado, Capoeiras, Jucati, Jurema, Jupi and Lajedo are partially inserted in the basin. In Alagoas, the municipalities of Murici, União dos Palmares, São José da Laje, Santana do Mundaú, Satuba and Branquinha have a part in the basin.

According to Brazilian Institute of Geography and Statistics (IBGE), the entire population living in the municipalities inserted in the Mundaú River Basin totaled 1,810,171 people in 2017. The largest population was in the municipality of Maceió, capital of Alagoas, with 1,029,129 inhabitants. The smallest population was in the municipality of Coqueiro Seco, also in Alagoas, with 5,918 people.

The MRB is predominantly rural, has substantial agricultural activity, including, a large dairy and broilers breeding industry. It also has substantial sugarcane production and processing industry. The MRB also has areas of Caatinga vegetation, characterized by seasonally dry shrubs and forests (Leal et al., 2005), as well as Atlantic Forest vegetation, characterized by seasonally dry and tropical forests (Werneck, 2011). Mangroves and coastal vegetation are also found in the region.

In relation to conservation areas, the Municipal Environmental Defense Council (CODEMA) of the Garanhuns, created in 2011, the Municipal Natural Park of the Mundaú Springs. The main spring is located in Fazenda Trindade. There are conservation areas also in Lagoa do Ouro, the Pedra Talhada Biological Reserve (Atlantic Forest) and in Lajedo, the Private Reserve of Natural Patrimony (Caatinga) (Araújo et al., 2015).

The soil classes existing in the MRB are Argisols, Gleysols, Latosols, litholic Neosols, fluvic Neosols, regolitic Neosols, Planosols and mangrove soils (Gomes et al., 2016). In general, the Argisols comprise soils composed of mineral material, increase in the clay content of the superficial horizon to the horizon B, present variable depth, are from strong to imperfectly drained. The Gleysols are hydromorphic soils, made up of mineral material, and with a horizon within the first 150 cm of the surface. The Latosols are deep soils, in advanced stage of weathering, very developed, constituted by mineral material, vary of strongly to well drained. The Neosols are composed of mineral material or organic material with a thickness of less than 20 cm, without the presence of the B horizon. The Planosols are mineral soils, imperfectly or poorly drained, it presents a very marked differentiation between the horizons A or E and B (EMBRAPA, 2006).

2.2 Climate zones

Most of the MRB is classified, in relation to amount of rainfall, as semi-humid and a small portion classified as semiarid, resulting, according to the IBGE, in two climatic zones, the tropical zone of the eastern Northeast and the tropical equatorial zone. The humid climate has high temperatures in the summer, reaching up to 40 ºC and in the winter reaches up to 18 ºC, but most of the year concentrates high temperatures (Araújo et al., 2015).

The region presents a climate, according to the classification of Köppen, Aw (Tropical, with dry season in winter), being a small portion to the northwest of the basin composed by the BSh climate (climate dry and semiarid, with low latitudes and altitudes) (Alvares et al., 2014).

The MRB climate is influenced by the Intertropical Convergence Zone (ZCIT in Portuguese), in the months of March and April, or in February and May, while the Eastern Systems interfere in the border with the Zona da Mata producing intense rainfall also in the coastal. There are still, the Cyclonic Vortexes of Superior Air (VCAS in Portuguese), in the months of November to February, which cause intense rains and severe droughts throughout the Pernambuco State. Finally, there are the breezes, that operate in the coastal zone and in the Zona da Mata during the year (Araújo et al., 2015).

2.3 Pluviometric and fluviometric characteristics

The average annual rainfall ranges from 497 to 1,143.63 mm (Araújo et al., 2015). In the coastal region of the basin, rainfall values can reach up to 2,000 mm, due to the influence of sea breezes and global atmospheric systems that bring more moisture to the continent, causing a higher concentration of rainfall in this area (Gomes et al., 2016). The average annual rainfall in the MRB is of 800 mm (Alvares et al., 2014), with precipitation declining as the distance from the coast increases. The rainy season is in the months of March to June (Araújo et al., 2015).

The Mundaú River, is born in the municipality of Garanhuns, Pernambuco State, and has about 70 km passing through the Pernambuco, entering the State of Alagoas by the Escada waterfall, south of the municipality of Correntes, and northwest of the municipality of Santana do Mundaú, crossing the central area of Atlantic Forest to flow into the Atlantic Ocean, near the Mundaú Lagoon (Araújo et al., 2015).

According to the APAC, the main tributaries of the Mundaú river in the state of Pernambuco are: on the right, Conceição stream, Salgado stream, Correntes river and Mundauzinho river; and, on the left, the Canhoto river. The most important tributary of the Mundaú River is the Canhoto river, which flows into the Mundaú River in Alagoan territory. The average monthly streamflow of the basin (2003 to 2016), according to the National Water Agency (ANA), is approximately 28 $m^3\ s^{-1}$ (at the Rio Largo station, located in the basin downstream).

The basin has great relevance because it presents high hydrological variability. There were episodes of peaks flows with flood problems, such as that in Santana do Mundaú, Alagoas, in 2010, causing damage in several areas. The basin also has experienced severe droughts, since part of it is already in the semiarid portion of Pernambuco, such as the recent exceptional drought of 2012, the highest of the last 50 years. The Mineral Resources Research Company (CPRM) launched in December 2017 the Mundaú River Hydrological Alert System. This is the 12th warning system launched by CPRM, being managed in partnership with the National Water Agency (ANA), with the support of the Secretariat for the Environment and Water Resources of Alagoas State (SEMARH) and the Pernambuco State Agency for Water and Climate (APAC). It is an extremely important system for regions such as MRB, which suffers from flooding and needs a warning and prevention support tool.

In relation to groundwater, according to the CPRM, through the project Register of Groundwater Supply Sources, made in 2005, there are a total of 810 wells along 34 municipalities of the MRB, of which 80 are from natural sources, 55 are excavated wells, 673 represent tubular wells, and two are not identified.

References

Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M., Sparovek, G., 2014. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift, 22, 6, 711–728. https://doi.org/10.1127/0941-2948/2013/0507.

Araújo, M.S., Araújo, H.M., Silva Júnior, C.G., 2015. Indicadores socioambientais e aplicabilidade no alto curso da bacia hidrográfica do rio Mundaú-PE. Revista Eletrônica em Gestão, Educação e Tecnologia Ambiental, 19, 1, 1-10. http://dx.doi.org/10.5902/2236117013111.

EMBRAPA. Centro Nacional de Pesquisa de Solos (Rio de Janeiro, RJ). Sistema brasileiro de classificação de solos. 2. ed. – Rio de Janeiro: EMBRAPA-SPI, 2006. 306 p. ISBN 85-85864-19-2.

Gomes, D.D.M., Lima, D.R.M., Veríssimo, C.U.V., Duarte, C.R., 2016. Mapeamento e caracterização dos sistemas ambientais da bacia hidrográfica do Rio Mundaú - PE/AL. Caderno de Geografia, 26, número especial 2, 272-299. http://dx.doi.org/10.5752/p.2318-2962.2016v26 nesp2p272.

Leal, I.R., Silva, J.M.C., Tabarelli, M., Lacher Junior, T.E., 2005. Changing the course of biodiversity conservation in the Caatinga of northeastern Brazil. Conservation Biology, 19, 701-706. http://dx.doi.org/10.1111/j.1523-1739.2005.00703.x.

Werneck, F.P., 2011. The diversification of eastern South American open vegetation biomes: Historical biogeography and perspectives. Quaternary Science Reviews, 30, 1630-1648. https://dx.doi.org/10.1016/j.quascirev.2011.03.009.

3. Soil and Water Assessment Tool (SWAT)

3.1 Definition and processing

The Soil Water Assessment Tool (SWAT) is a hydrological and sedimentological model that was developed by Dr. Jeff Arnold and his team at the Agricultural Research Service of the United States Department of Agriculture (ARS – USDA) to analyze the impacts of land use changes on water runoff, sediment yield and water quality in large ungauged watersheds (Arnold et al., 1998). SWAT is a versatile model that considers different hydrological and agronomic components and has been applied by many governmental and private institutions, as well as universities and other institutions interested in supporting decision-making in the management of water resources (Bressiani et al., 2015).

The creation of the model occurred in the 1990s and from there the model was continuously improved, resulting in new versions: SWAT 94.2, SWAT 96.2, SWAT 98.1, SWAT 99.2, SWAT 2000 and SWAT 2009. Among the most significant improvements of the model, one that we can highlight is the association with the Geographic Information System (GIS), such as the ArcGis™ (Enviromental Systems Research Institute – ESRI 1998). When using ArcGIS software, SWAT becomes ArcSWAT (Pinto, 2011). The last update of the SWAT model (version 2012) was in 2013 and it is available for download on the official website of the model: http://swat.tamu.edu/.

The SWAT classification is semi-conceptual, semi-distributed, continuous-time, process based hydrology and water quality model that uses a daily time step and multiple hydrologic units to simulate different physical processes within the study area, as such as climate, hydrology (surface runoff, percolation, interception, infiltration, subsurface flow, baseflow and evapotranspiration), soil moisture, plant growth, nutrients, pesticides, bacteria and pathogens, and soil management (Arnold et al., 2012).

The hydrological cycle in SWAT is based on the water balance equation (Eq. 1) (Arnold et al., 1998):

$$SW_t = SW_0 + \sum_{i=1}^{t}(P - Q_s - ET - W_s - Q_{gw}) \quad (1)$$

Where: SW_t is the final soil water content in time t (mm) and SW_0 is the initial soil water content in time t (mm); t is time (days), P is precipitation in time t (mm), Q_s is surface runoff in time t (mm), ET is the actual evapotranspiration in time t (mm), W_s is percolation in time t (mm) and Q_{gw} is the baseflow in time t (mm) (Neitsch et al., 2005).

The soil profile can be divided into up to 10 layers, each layer being considered uniform, that is, the soil can be considered as homogeneous (one soil layer) or heterogeneous (more than one layer of soil) (Pereira, 2013). At the beginning of hydrological modeling with SWAT, the watershed is divided into several sub-basins and the amount of these depends on the minimum drainage area. With the finalized delimitation, the model makes combinations between land use, soil types and slope, establishing the Hydrological Response Units (HRUs). Estimates of evapotranspiration as well as surface runoff are predicted separately for each HRU to enable better physical representation of hydrological processes (Strauch et al., 2012). Figure 1 shows the representation of the water balance components simulated by the SWAT model in each soil layer.

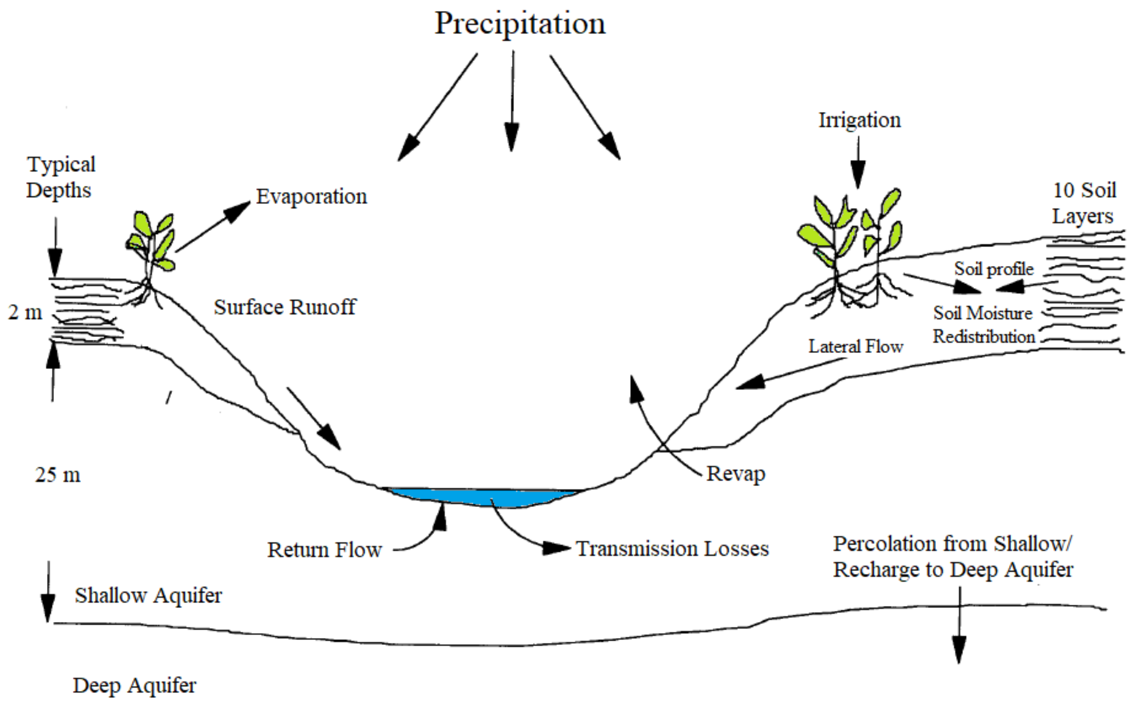


Fig. 1. Components of the hydrologic balance of the SWAT model (Adapted from Arnold et al., 1998)

The generation of surface runoff in a watershed occurs when the amount of water applied to the soil exceeds its infiltration rate. When the soil is in dry conditions, there is usually a high rate of infiltration and this rate decreases as the soil becomes wetter (Neitsch et al., 2011). When the soil reaches surface saturation and continues to be saturated at greater depths, the infiltration rate becomes residual and the non-infiltrated excess of precipitation leads to flow generation (Cordero, 2013).

The SWAT model provides two methods for estimating runoff: The Soil Conservation Service (SCS, 1972) Curve-Number method and the Green and Ampt (1911) infiltration method. The Curve-Number method, which is linked to the United States Department of Agriculture (SCS – USDA), is the standard method used by SWAT. From this method it is possible to perform an estimation of the surface runoff blade, considering precipitation data and parameters that characterize the basin (Pruski et al., 2008). The flow equation proposed by SCS is an empirical method that had the 1950s as the beginning of its frequent use. The model was created with the purpose of suggesting a consistent basis in estimating the surface runoff in different land use conditions and soil types (Rallison and Miller, 1981).

According to the Curve-Number method, the accumulated precipitation varies linearly with time, that is, the precipitation intensity is considered constant for a given duration of rainfall (Figure 2). Until the time t_{Ia}, all the precipitation incident is converted into initial abstractions. These abstractions include surface storage, interception, and infiltration before runoff. When initial abstractions finish, surface runoff begins (Pruski et al., 2008).

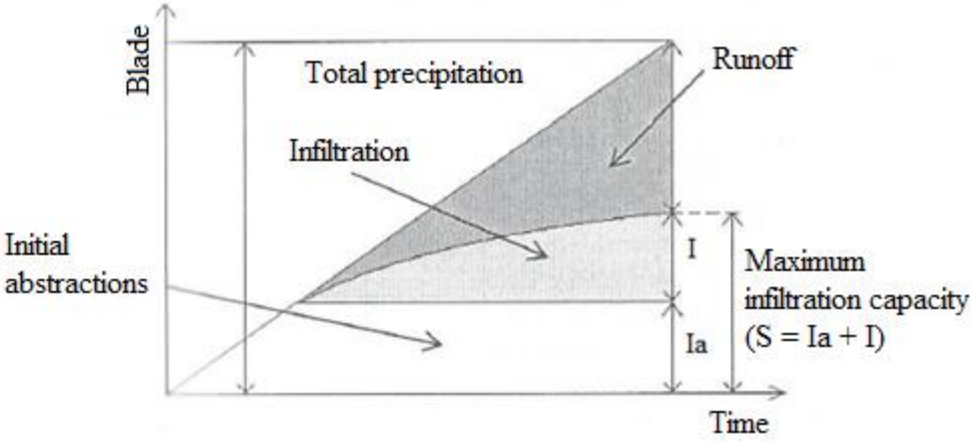


Fig. 2. Components associated with the Curve-Number method - SCS (Pruski et al., 2008).

Surface runoff is given by (Rallison and Miller, 1981):

$$Q_s = \frac{(P - I_a)^2}{P - I_a + S} \qquad (2)$$

Where: I_a includes surface storage, interception and infiltration before discharge (mm), commonly approximated to 0.2 in the numerator and to 0.8 in the denominator; S is the water retention parameter (mm), which varies spatially according to soil type, vegetation cover, management and declivity, and CN is the Curve Number (Eq.3):

$$S = 25{,}4\left(\frac{1000}{CN} - 10\right) \quad (3)$$

The Curve-Number (CN) parameter varies as a function of soil permeability, land use and soil antecedent moisture conditions. The SCS-USDA provides, through tables, different values for the CN. The types of soils identified in these tables are as follows (Pruski et al., 2008; Tucci, 2013): 1. Soil A: Soils that have low runoff and high infiltration rate. Soils sandy, deep, with low levels of silt and clay. 2. Soil B: soils less permeable than type A, but with above-average permeability. Sandy soils with moderate depth. 3. Soil C: soils capable of generating above-average flow and low infiltration rate. They have considerable amount of clay and are shallow. 4. Soil D: very low infiltration capacity, resulting in a high flow potential. Shallow soils containing expansive clays.

The antecedent moisture conditions are as follows (Tucci, 2013): 1. AMC I - soils present in dry conditions, with moisture at the wilting point (PMP). The accumulated precipitation of the previous five days is less than 36 mm in the growing season and less than 13 mm in another season. 2. AMC II - soils present in the average condition, with the moisture in the field capacity (CC). 3. AMC III - soils under saturation conditions. The accumulated precipitation of the previous five days is greater than 53 mm in the growing season and greater than 28 mm in another season.

The Green and Ampt method was created with the purpose of determining the infiltration of water into the soil assuming the existence of water excess in the surface at all times (Green & Ampt, 1911). The model considers a homogeneous soil profile and an antecedent moisture consistently distributed in the profile. As water infiltrates into the soil, the method assumes that the above-the-wetting layer is completely saturated and there is an abrupt change in soil moisture in front of wetting. The difference in the distribution of the water content modeled by Green and Ampt and a typical observed distribution (as it happens in reality) is illustrated in Figure 3 (Neitsch et al., 2011).

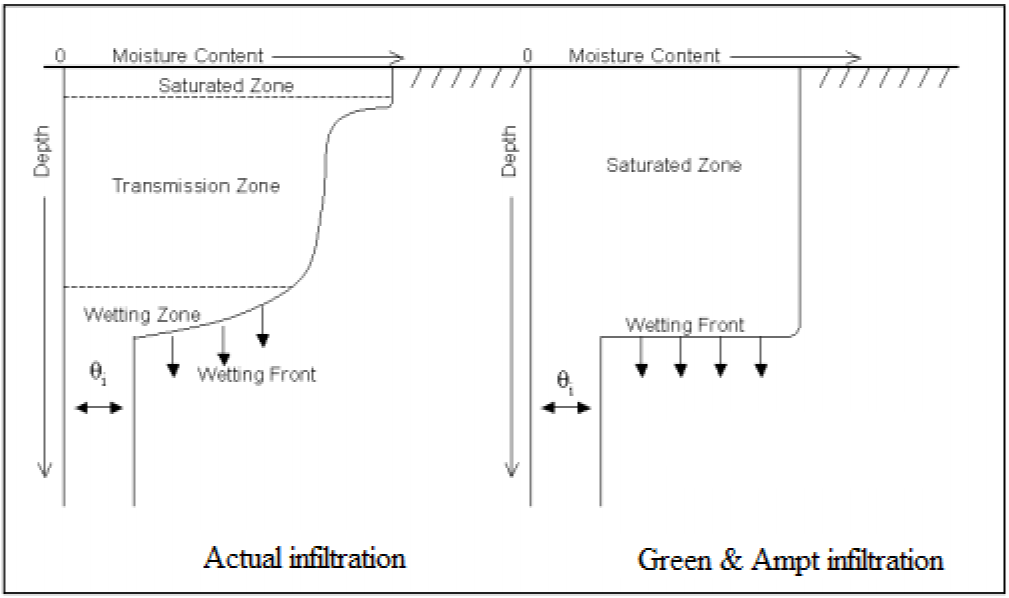


Fig. 3. Comparison of water content distribution simulated by Green and Ampt and a real observed distribution (Neitsch et al., 2011)

A methodology proposed by Mein and Larson (1973) combined with the Green-Ampt method was incorporated into the SWAT model to provide another alternative in the determination of surface runoff. The Mein-Larson Green-Ampt infiltration rate is defined as:

$$f_{inf,t} = k_e . \left(1 + \frac{\Psi_{wf} . \Delta\theta_v}{F_{inf,t}}\right) \tag{4}$$

Where: f_{inf} is the infiltration rate at time t (mm h^{-1}), k_e is the effective hydraulic conductivity (mm h^{-1}), ψ_{wf} is the matrix potential of the wetting front (mm), $\Delta\theta_v$ is the change in soil volumetric moisture through the wetting front (mm mm^{-1}) and F_{inf} is the cumulative infiltration at time t (mm).

The peak flow, that is, the maximum runoff rate in a given rainfall event, is calculated by the SWAT model from the rational method. The rational method considers that a certain rainfall with intensity i beginning at time t, will have its discharge rate increased until reaching the concentration time t_{conc}. The method is given by the following equation (Neitsch et al., 2005):

$$q_{peak} = \frac{C * i * A}{3{,}6} \qquad (5)$$

Where: q_{peak} is the peak flow rate (m^3 s^{-1}), C is the runoff coefficient, i is the precipitation intensity (mm h^{-1}) and A is the watershed area (km^2).

In relation to the calculation of infiltration rate, when the Curve-Number method is adopted, the SWAT model considers that the quantity of water entering the soil profile is the difference between the rainfall and the surface runoff. The Curve-Number method cannot simulate the infiltration rate because it operates in a daily time step. The Green and Ampt method, on the other hand, requires sub-daily precipitation data, and therefore can directly simulate infiltration (Neitsch et al., 2011).

The redistribution component of SWAT model uses a storage routing technique to simulate flow through each soil layer in the root area. The percolation occurs when field capacity is exceeded and the layer below is not saturated (Neitsch et al., 2011). When this water is lost from the watershed, becomes groundwater or appears as return flow (Arnold et al., 1998). The storage routing technique is given by the following equation (Neitsch et al., 2011):

$$SW_i = SW_{ei} exp\left(\frac{-\Delta t}{TTi}\right) \tag{6}$$

Where: SW_i is the final soil water content in time t (mm) and SW_{ei} is the initial soil water content in time t (mm); $\triangle$t is the time interval (24h); TT_i is the travel time (h) through the layer i. The percolation can be computed by (Neitsch et al., 2011):

$$O_i = SW_{oi}\left[1 - exp\left(\frac{-\Delta t}{TTi}\right)\right] \tag{7}$$

Where O is the percolation rate (mm d^{-1}).

The travel time (TT_i) is calculated for each soil layer by the linear storage equation (Neitsch et al., 2011):

$$TTi = \frac{(SWi - FCi)}{Hi} \tag{8}$$

Where: H_i is the hydraulic conductivity (mm h^{-1}) and FC_i is the field capacity minus wilting point water content for the layer i (mm).

The lateral subsurface flow is calculated in SWAT model simultaneously with the percolation. A kinematic storage model (Sloan et al., 1983) is used by the model:

$$q_{lat} = 0.024 \frac{(2\ S\ SCi\ sin(\alpha))}{\theta_d L} \tag{9}$$

Where: q_{lat} is lateral flow (mm d^{-1}), S is drainable volume of soil water (m h^{-1}), SC_i is the saturated conductivity for layer i (mm h^{-1}), α is slope (mm^{-1}), θ_d is drainable porosity (mm^{-1}) and L is flow length (m). Thus, the groundwater flow that contributes to total streamflow is simulated by creating a shallow aquifer storage (Neitsch et al., 2011).

In relation to the calculation of potential evapotranspiration (ET_0), the SWAT model offers three options for estimating this component: Penman-Monteith-FAO, Hargreaves & Samani and Priestley-Taylor methods. The standard method of the model is the Penman-Monteith-FAO, which requires meteorological variables as such as solar radiation, air temperature, relative humidity and wind speed to estimate ET_0 (Neitsch et al., 2005). The Priestley-Taylor method provides potential evapotranspiration with temperature and radiation data. The Hargreaves & Samani method in SWAT requires only maximum and minimum temperatures data (Arnold et al., 1998). In the present study, the Hargreaves & Samani method was adopted, as it requires only radiation and temperature data, and it fits very well for semiarid regions.

In relation to the researches performed with the SWAT model, an extensive number of analyzes have already been carried out worldwide, including studies on different climate change scenarios, land use change scenarios, improved irrigation strategies, application of best management practices (BMPs), the use of bioenergy crops, the transport of nutrients, pesticide pollution and sediment transport (Gassman et al., 2014). According to Bressiani et al. (2015), between 1999 and 2013, at least 102 publications (articles in journals, papers in congresses, monographs, dissertations and theses) including the SWAT model were verified in Brazil. Among these works, the small basin simulated by SWAT had 0.1 km², an experimental basin of Rio Negro, State of Santa Catarina; and the largest had 29,000 km², the catchment area of the Cuiabá River, in Mato Grosso.

In relation to other hydrological models, SWAT has the advantage of efficiently simulating a data series of several years, even if operating in daily time conditions, and can be considered a long-term simulation model (Arnold et al. 1998). It is considered a computationally efficient model, simulating basins in small and large scales in a rapid way and allows the simulation of the effects of changes in land use over extended periods of time (Arnold et al., 1998; Neitsch et al., 2005).

However, the disadvantages of the model are in the fact that the model requires daily precipitation data (which are not readily available), uses an empirical equation (Curve-Number method) in the simulation of the surface runoff, not evaluating the precipitation intensity, presents difficulties in relation to the spatial variability associated with precipitation in the modeling of large areas, among others (Arnold et al., 1998). Another difficulty is that the SWAT does not simulate the occurrence of floods and sediment considering detailed events (Pereira, 2013). Even presenting some difficulties, Blainski et al. (2011) emphasize the importance of the development of tools such as SWAT, due to the expansion of agricultural activities, associated with the degradation and contamination of water resources, aiming at the sustainable use of natural resources.

3.2 Input data

The SWAT model requires four main types of input data, including three maps, which are Digital Elevation Model (DEM), land use map and soil type map, and a series of meteorological data, as such as: precipitation, maximum and minimum air temperatures, relative humidity, wind speed and solar radiation. Information from several public agencies was collected for the modeling process in the Mundaú River Basin. The agencies include the National Water Agency (ANA), the Pernambuco Agency for Water and Climate (APAC), the Secretariat of Environment and Water Resources of the state of Alagoas (SEMARH), the National Institute of Meteorology (INMET), the Brazilian Agricultural Research Corporation (EMBRAPA), Brazilian Institute of Geography and Statistics (IBGE), RADAMBRASIL Project, Shuttle Radar Topography Mission (SRTM), LANDSAT Satellite, Environment Ministry of Brazil (MMA), National Supply Company (CONAB), Secretariat of Water and Energy Resources (SRHE) and the Mineral Resources Research Company (CPRM). In addition, published articles, theses, dissertations, experts in the field of study, such as local farmers, professors, and agency professionals were consulted. More information on the sources of obtaining the database for the application of the SWAT model in Brazil can be obtained in Bressiani et al. (2015).

The Digital Elevation Model (DEM) was obtained from Shuttle Radar Topography Mission (SRTM), available at https://www.cnpm.embrapa.br/projetos/relevobr/download/, where there are archives of the altimetry of Brazil. The images are Geotiff format (16 bits), with spatial resolution of 90 m and WGS-84 Geographic Coordinate System (Figure 4).

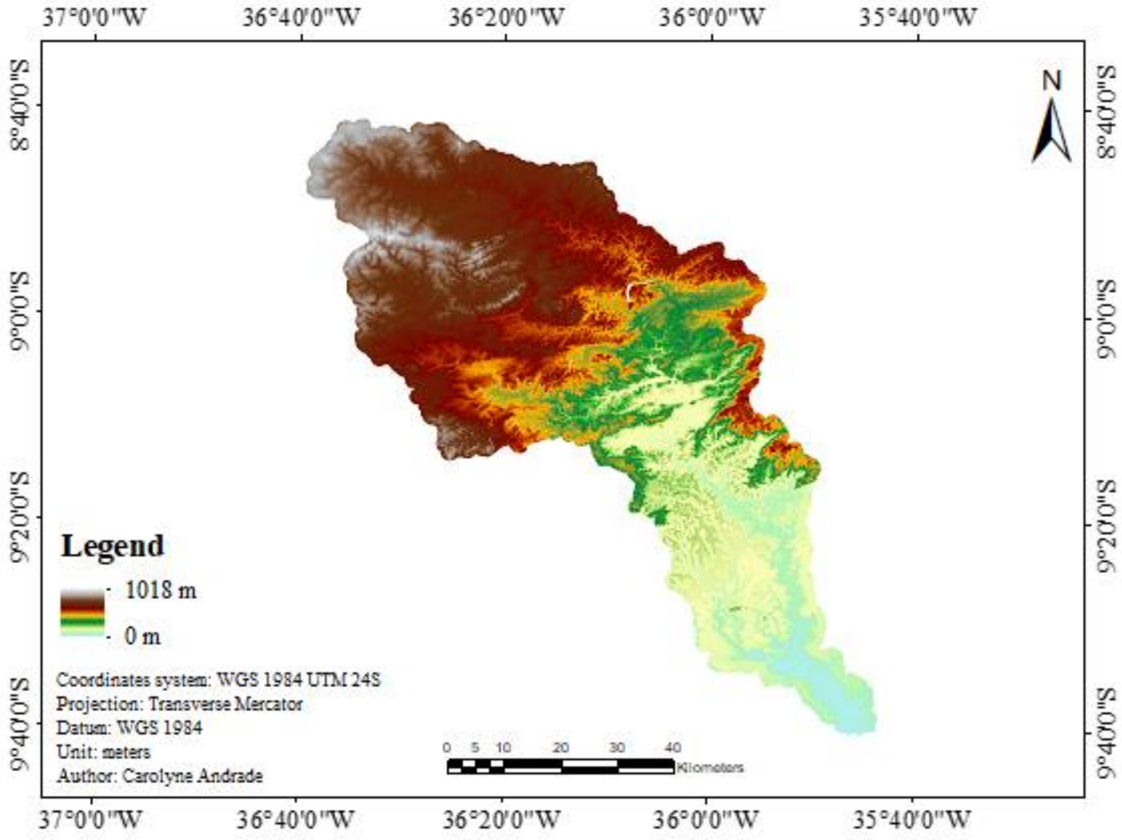


Fig. 4. Digital Elevation Model (DEM) of the Mundaú River Basin

The land use map of the Mundaú River Basin (Figure 5) was elaborated using digital image and image processing tools from LANDSAT 5 satellite, TM instrument, with approximately 30 m resolution and Orbits / Point 214/66, 214/67 and 215/66 referring to the year of 2011, obtained from the National Institute for Space Research (INPE) and available at http://www.dgi.inpe.br/CDSR/. The imagery has been processed using ENVI™ software. Initially, images were converted into Universal Transfer Mercator and geo-referenced to a datum in which Brazil has been selected by WGS 84. The mapping was performed using the supervised classification method, adopting the maximum likelihood classifier. In addition, information was used from the Environment Ministry of Brazil (MMA) and the National Supply Company (CONAB).

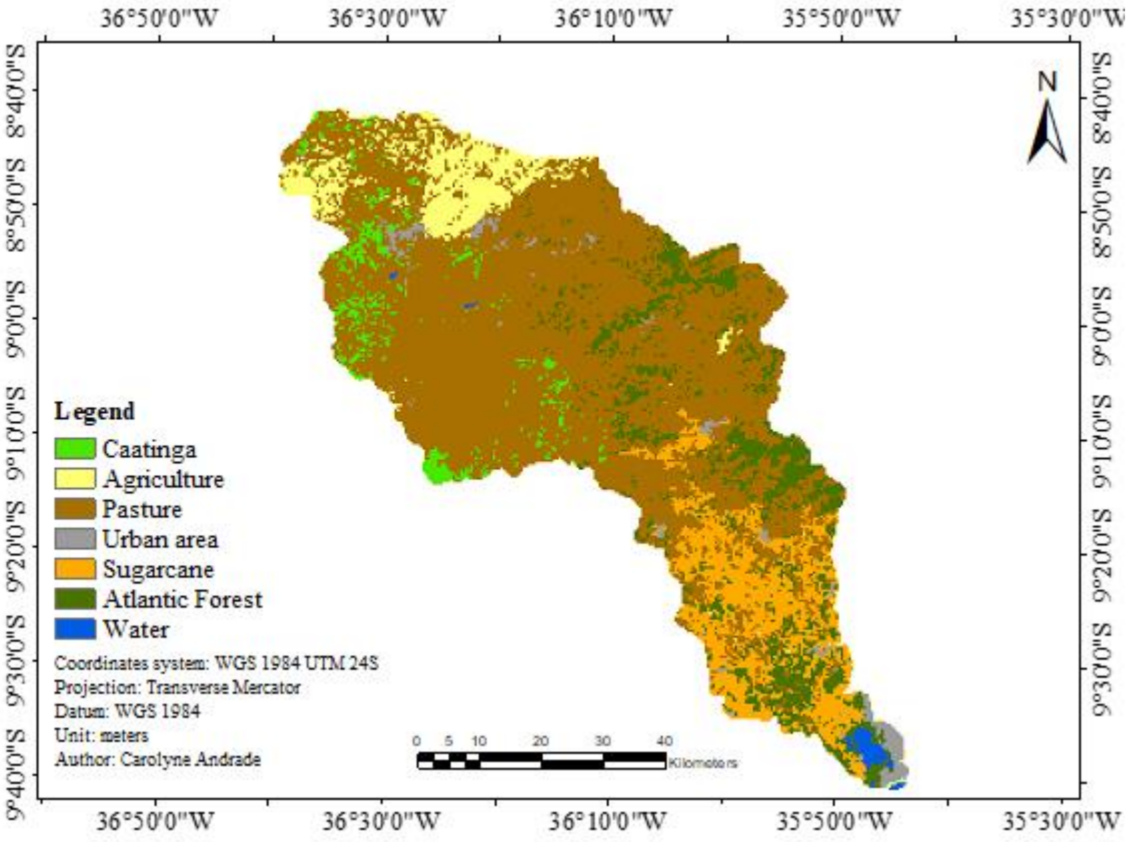


Fig. 5. Land use map of the Mundaú River Basin

Land use was divided into seven classes of interest: i) Water, ii) Urban Area, iii) Caatinga, iv) Atlantic Forest, v) Pasture, vi) Sugarcane, and vii) Agriculture. For the characterization of the land use in MRB, the information contained in the SWAT database, which has multiple types of land use and vegetation cover, was associated with the classes obtained. These data were customized according to the characteristics of the crops in Brazil (Table 1).

Table 1. Association of existing land uses in the study with existing uses in the SWAT database

Number	Land use in the MRB	SWAT Database
1	Water	Water (WATR)
2	Urban area	Residential (URBN)
3	Caatinga	Range Brush (RNGB)
4	Atlantic Forest	Forest-Evergreen (FRSE)
5	Pasture	Pasture (PAST)
6	Sugarcane	Sugarcane (SUGC)
7	Agriculture	Agricultural Land-Generic (AGRL)

The soil types map (Figure 6) was obtained from data provided by the Brazilian Agricultural Research Corporation (EMBRAPA), based on the information provided by the Agroecological Zoning of Pernambuco (ZAPE) and Alagoas (ZAAL), which provides maps in the scale of 1: 100,000. The soils existing in the MRB are, in the majority, yellow Argisols and red-yellow Argisols; there are also Neosols, Latosols, Planosols, and Mangrove soils.

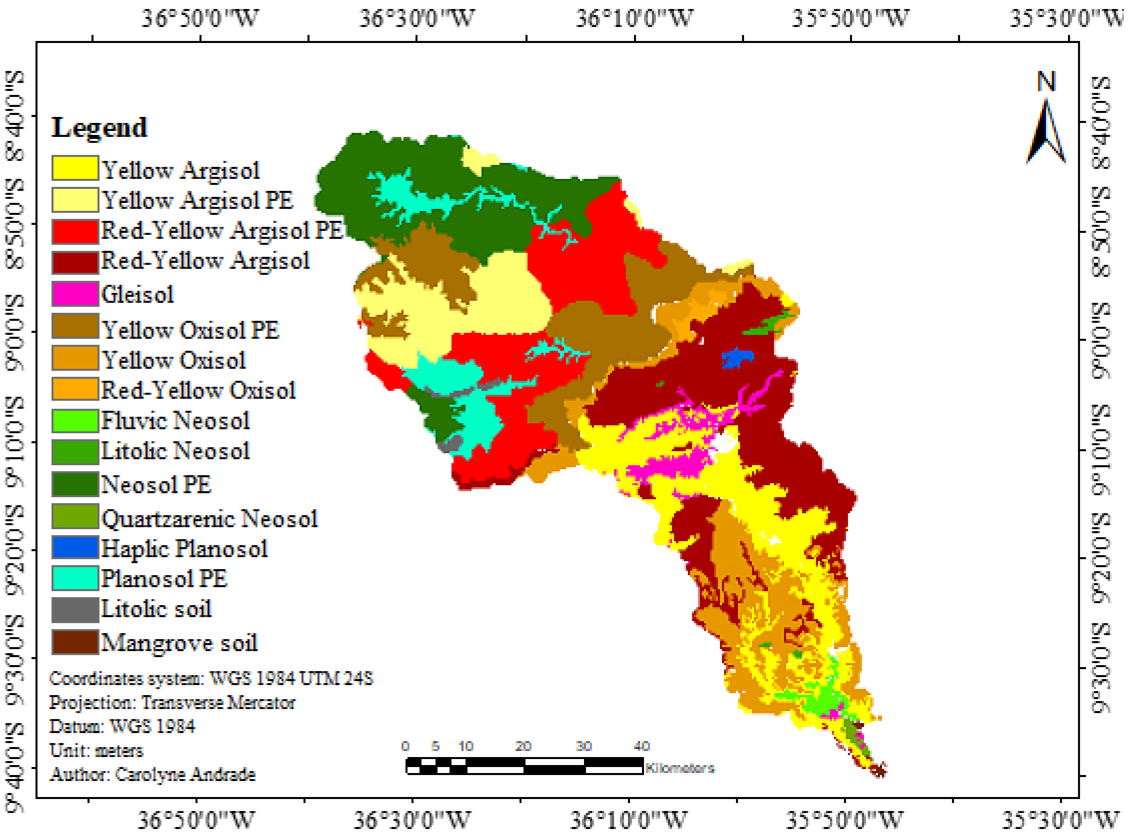


Fig. 6. Soil type map of the Mundaú River Basin

As shown in Figure 6, the basin is predominantly composed of the Argisols, the Neosols and the Latosols. The physical and chemical properties of each soil are required by the SWAT model in two steps: i) soil type parameters, which involve name, number of layers, hydrological group, soil depth and porosity; and (ii) soil layer parameters, which include layer depth, soil density, available water capacity, organic carbon and saturated hydraulic conductivity (Fetter, 1988); granulometry, rock percentage, albedo and layer erodibility factor. The physical soil parameters required by the SWAT model were calculated from pedotransfer functions developed by Saxton and Rawls (2006). Pedotransfer functions are predictor functions that relate soil hydraulic and physical-chemical characteristics to the basic soil properties, such as texture and organic matter. These functions were developed due to the fact that some parameters are difficult to estimate with accuracy, such as saturated hydraulic conductivity, besides the need for time and cost demands (Obiero, 2013). The texture and organic matter information needed to use these functions were obtained in the literature, as shown in Table 2.

Table 2. References used to collect soil physical and chemical parameters

Number	Soil Type	State	Reference consulted
1	Yellow Argisol	AL	Silva et al. (2012)
2	Yellow Argisol	PE	Oliveira & Nascimento (2006)
3	Red-Yellow Argisol	PE	Oliveira & Nascimento (2006)
4	Red-Yellow Argisol	AL	Projeto RADAMBRASIL
5	Gleisol	AL	Silva et al. (2012)
6	Yellow Oxisol	PE	Araújo et al. (2015)
7	Yellow Oxisol	AL	Silva et al. (2012)
8	Red-Yellow Oxisol	AL	Projeto RADAMBRASIL
9	Fluvic Neosol	AL	Projeto RADAMBRASIL
10	Litolic Neosol	AL	Projeto RADAMBRASIL
11	Neosol	PE	Oliveira & Nascimento (2006)
12	Quartzarenic Neosol	AL	Silva et al. (2012)
13	Haplic Planosol	AL	Projeto RADAMBRASIL
14	Planosol	PE	Parahyba et al. (2010)
15	Litolic soil	PE	Oliveira & Nascimento (2006)
16	Mangrove soil	AL	Projeto RADAMBRASIL

The hydrological and meteorological data were collected from ANA, APAC and INMET agencies. The stations as well as their locations are presented in Figure 7. We selected 19 rainfall stations, inserted in 11 municipalities of the Mundaú River Basin, 5 fluviometric stations, inserted in 5 municipalities of Alagoas, and 2 meteorological stations, inserted in the Garanhuns and Maceió municipalities.

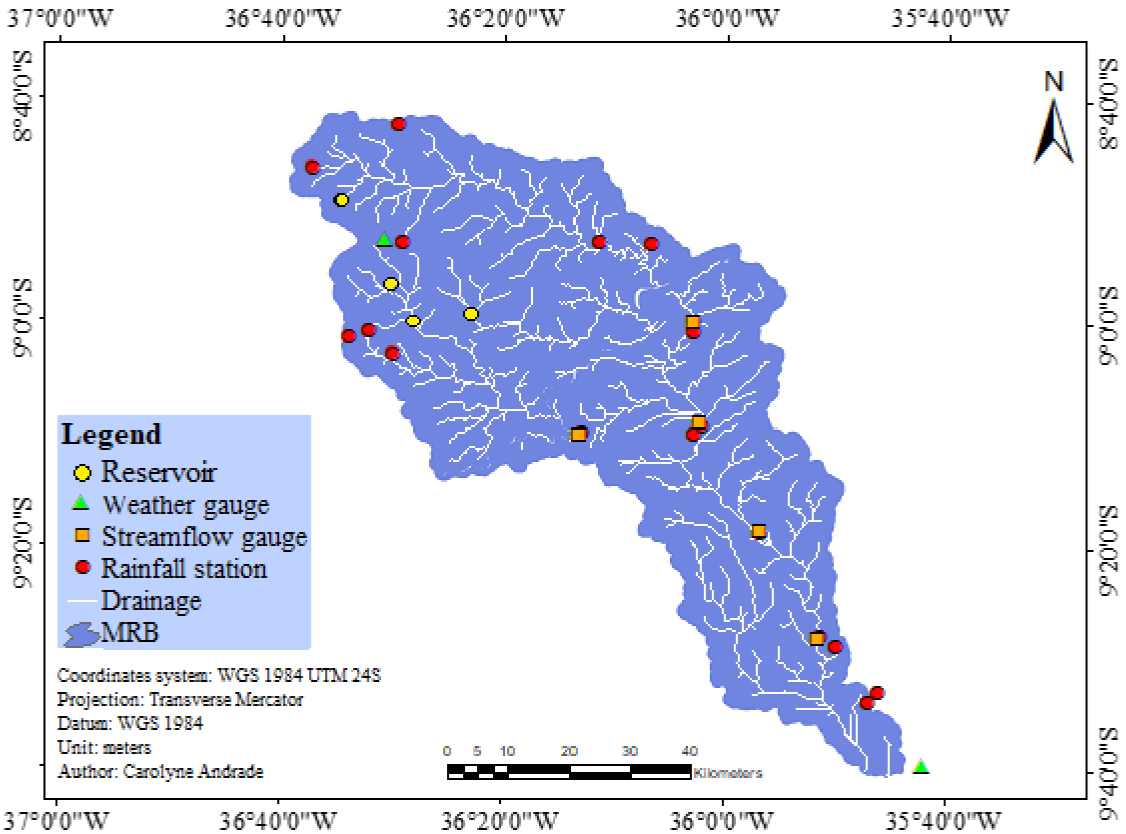


Fig. 7. Hydrological and meteorological stations, and reservoirs of the Mundaú River Watershed

In addition, data provided by two stations located in strategic areas of the basin, under the responsibility of the Federal Rural University of Pernambuco - Garanhuns Academic Unit, were also used. The stations are located at Fazenda Riacho do Papagaio, municipality of São João – PE. One station is inserted in an area of 16 ha of pasture and the other in an area occupied by 4 ha of Caatinga vegetation. The information used includes daily data of soil moisture (m^3 m^{-3}) of the station inserted in the pasture area.

Regarding the data availability for the Mundaú River Basin, there are rainfall data since the 1920s; however, when the amount of precipitation data was verified in each year and in each station, were detected years with high failure percentages, especially the oldest years. A refinement was made in order to select the years that have an annual failure rate of less than 50%. In this way, the years above 50% were discarded. The procedure was performed in such a way that all the stations of the basin resulted in the same series of rainfall data., until verifying that the period considered acceptable for hydrological modeling with the SWAT model is from 2000 to 2016, constituting 17 years of data.

The remaining failures (<50%) in the selected years were corrected using a tool called Windows Precipitation - WinPreci, developed by Silva (2015). The WinPreci program was developed to access (resolution of approximately 1 km^2) and to present the spatial distribution of precipitation, based on monthly rainfall information provided by the Institute of Technology of Pernambuco (ITEP) and the National Institute of Meteorology (INMET). The objective of this tool is to assist studies related to agricultural, water resources, environmental and socioeconomic policies for the Pernambuco State (Silva, 2015). The author completed monthly rainfall data from the application of the Inverse Distance Weighting (IDW) spatial interpolation method (Shepard, 1968) at several stations in the State of Pernambuco, from 1950 to 2012. The IDW is one of the methods more adopted in studies involving Geographic Information Systems (GIS), and combines the concepts of interpolation defined by Thiessen (1911), with a gradual change over the entire interpolated surface. The method considers a linear combination based on the near points to estimate the non-sampled location, and weights are assigned to the points, with the highest weights to the nearest and the lowest to the farthest points. WinPreci allows the access and visualization of these data through maps and numerical values. As SWAT requires daily precipitation data, Silva (2015), particularly for MRB, developed a routine where missing data from the database was filled using the same method as that used by WinPreci.

In addition to the examination of the existing failures in the hydrological series, the consistency of precipitation data was checked for each station. According to Paca (2008), modifications of the position or exposure of a rainfall station can cause large changes in the amount of precipitation it measures, leading to inconsistent data. According to the Dual Mass method developed by the Geological Survey (USA), the graph corresponding to a certain period of accumulated rainfall when plotted together with data from one or more neighboring stations should result in a straight line. This method is widely adopted in Brazil and is valid for monthly and annual rainfall series. The consistency analysis for MRB rainfall stations are presented in Figures 8 and 9.

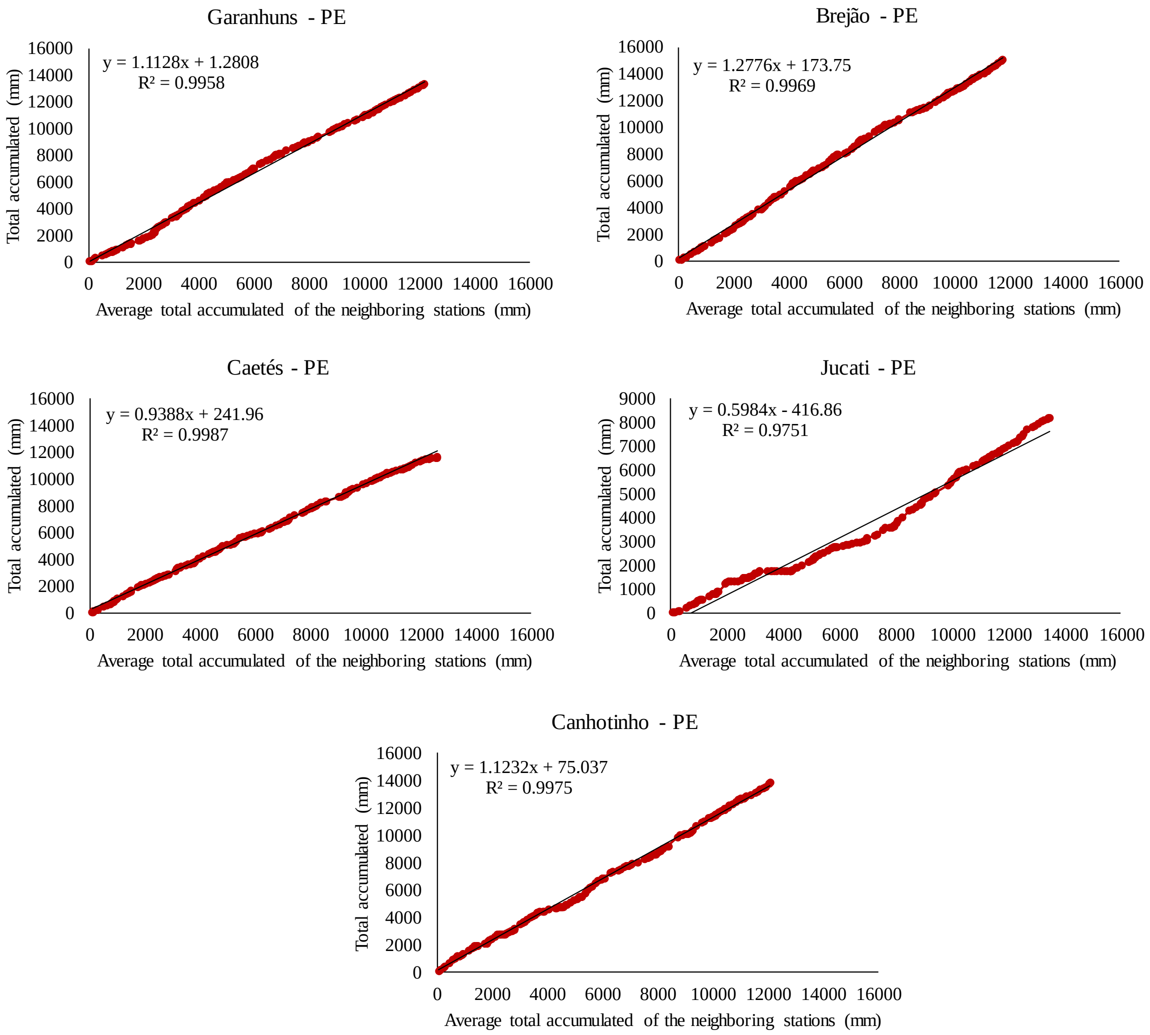


Fig. 8. Evaluation of consistency of rainfall series by Dual Mass method in the Pernambuco stations at Mundaú River Basin

It can be observed in Figure 8 that the all stations of the municipalities in Pernambuco (with the data period between 2000 and 2014) presented consistency, according to the Dual Mass method, with coefficients of determination above 0.9751. The stations of the municipalities in Alagoas also presented consistency, with coefficients of determination above 0.9856.

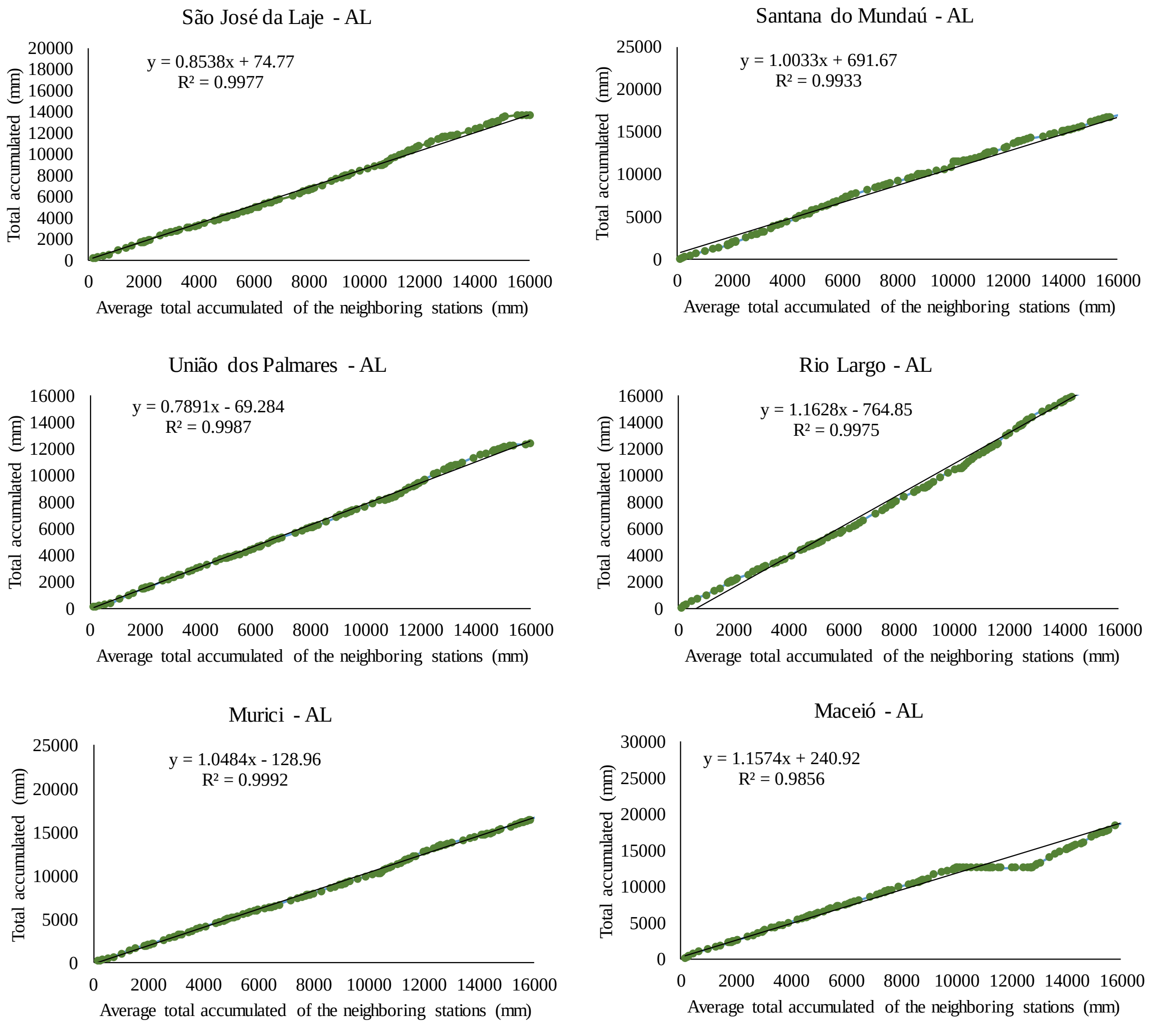


Fig. 9. Evaluation of consistency of rainfall series by Dual Mass method in the Alagoas stations at Mundaú River Basin

In relation to streamflow data, there are data since 1980, however, as well as precipitation data, the failures are accentuated in the older years, and the period from 2000 was considered good for modeling. For soil moisture data, there are records since 2011 in the studied area, representing a series of 7 years of extension. However, only 2 years of data were used, due to the better results obtained.

According to Strauch and Volk (2013), as the SWAT model was developed for temperate regions, it is extremely important to carry out a critical analysis of the differences between the standard values of the parameters of the model itself and the values of these variables for tropical regions, such as Brazil. In this way, some editions were added to the SWAT model, in order to better characterize the Mundaú River Basin. The information includes the insertion of some existing reservoirs along the basin, as well as information related to crop, forest and pasture management. Four reservoirs were inserted in the MRB, which were Cajarana, Mundaú, Mundaú II and Inhumas (Figure 7). The information regarding the reservoirs was obtained through the Secretariat of Water and Energy Resources (SRHE) and are presented in Table 3. In relation to the Mundaú II reservoir, the SWAT model considers this reservoir only from the beginning of its operation, which in the case was in 2010. Before that, it "does not exist" for the model. Thus, in the period before 2010, Mundaú II was not considered. In relation to the verification of the model response after the construction of the Mundaú II, it will be verified in the fluviometric station União dos Palmares (which considers the 4 reservoirs), since the validation period contemplates 1 year after the construction of the Mundaú II. The results of the model performance in the calibration and validation processes will be further detailed later in Chapter 4.

Table 3. Characteristics of existing reservoirs in the Mundaú River Basin

Number	Reservoir	Municipality	Start of operation	Maximum capacity (m³)
1	Cajarana	Garanhuns	2000	2,594,280
2	Mundaú	Garanhuns	1995	1,968,600
3	Mundaú II	Garanhuns	2010	19,283,196
4	Inhumas	Palmerina	1995	7,872,860

In relation to the managements adopted for the crops, vegetation and livestock existing in the MRB, some editions have been proposed. For agriculture, sugarcane and forests, begin and end of growing seasons were established through dates. In addition, some parameters were modified in relation to the standard adopted by the model. The method of calculation of potential evapotranspiration was also changed. All of these modifications improved the outputs of the model relative to the simulation without any editing. The updated values of the parameters are presented in Table 4.

Table 4. Values of the edited parameters in the SWAT model for the Mundaú River Basin

Number	Parameter	Description	Default value	Updated value
1	LAI_INIT	Initial leaf area index	0	2
2	BIO_INIT	Initial dry weight biomass (kg ha^{-1})	0	1,000
3	PHU_PLT	Total number of heat units or growing degree days needed to bring plant to maturity	0	2,500
4	ESCO	Soil evaporation compensation factor	0.95	0.6
5	MANURE_ID	Manure identification code from fertilizer database	Several options	Beef-Fresh Manure
6	GRZ_DAYS	Number of consecutive days grazing takes place in the HRU	0	270
7	BIO_EAT	Dry weight of biomass consumed daily ((kg ha^{-1}) day^{-1})	0	10
8	BIO_TRMP	Dry weight of biomass trampled daily ((kg ha^{-1}) day^{-1})	0	2
9	MANURE_KG	Dry weight of manure deposited daily ((kg ha^{-1}) day^{-1})	0	7
10	ET$_0$ calculation	Method for calculating potential evapotranspiration	Penman-Monteith-FAO	Hargreaves and Samani

3.3 Sensitivity analyses

The sensitivity analysis of the Mundaú River Basin parameters was performed using the SWAT Calibration and Uncertainty Programs (SWAT-CUP), an independent software developed for uncertainty and sensitivity analyzes, calibration and validation processes, using SWAT simulations. The program comprises five calibration procedures (SUFI-2, PSO, GLUE, ParaSol and MCMC), eleven goal functions (mult, sum, R2, chi2, NS, br2, ssqr, PBIAS, KGE, RSR, MNS) and includes applications such as visualization of the study area (Abbaspour et al., 2007). In this study, the sensitivity analysis was performed in the SWAT-CUP using the Sequential Uncertainty Fitting algorithm (SUFI-2). Additionally, the Nash-Sutcliffe (NS) coefficient was used as goal function.

A distributed or semi-distributed hydrological model is composed of a series of parameters that govern different processes. The sensitivity study was based on the analysis of parameters and input variables of the model, in order to observe those that, when altered, exert a significant influence on the results. Each parameter has minimum and maximum standard values, and such values can be found in the SWAT manual as well as in the literature, in addition to the knowledge values of the modeler. We selected 19 parameters related to the processes of flow, evapotranspiration, percolation, recharge, infiltration, among others, for a first analysis. The sensitivity analysis was performed considering a global sensitivity analysis with such parameters, in order to verify the ones that have the greatest influence and the most sensitive.

The sensitivity of the parameters is determined through the application of a multiple regression system, in which the parameters generated by the Latin Hypercubic Sampling are related to the objective function values. The t-test is used to identify the relative significance of each parameter, and the higher the value (in absolute terms) the parameter has, the more sensitive it will be. The p-value determines the significance of the sensitivity and values close to zero indicate the most significant parameters (Abbaspour, 2015). The results of the automatic sensitivity analysis for discharge, performed by SWATCUP, are presented in

Table 5. The table lists the SWAT parameter name, its description, and the sensitivity level ranking for the study area under the simulation conditions of the MRB.

Table 5. Automatic sensitivity analysis for discharge in the Mundaú River Basin

Ranking	Parameter	Description	t-Stat (absolute)	P-Value
1	CN2	Initial SCS runoff Curve Number for moisture condition II	4.28	0.0004
2	RCHRG_DP	Deep aquifer percolation fraction	3.38	0.0030
3	SOL_Z	Depth from soil surface to bottom of layer, mm	2.44	0.0241
4	OV_N	Manning’s “n” value for overland flow	2.35	0.0290
5	CANMX	Maximum canopy storage, mm H_2O	1.92	0.0695
6	LAT_TTIME	Lateral flow travel time, days	1.86	0.0773
7	REVAPMN	Threshold depth of water in the shallow aquifer for “revap” or percolation to the deep aquifer to occur, mm H_2O	1.58	0.1291
8	CNCOEF	Plant ET Curve Number coefficient	1.45	0.1623
9	ALPHA_BF	Baseflow recession constant, days	1.26	0.2209
10	GW_DELAY	Groundwater delay time, days	1.21	0.2418
11	SURLAG	Surface runoff lag coefficient	0.89	0.3844
12	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur, mm H_2O	0.65	0.5260
13	CH_N2	Manning’s “n” value for the main channel	0.49	0.6282
14	EPCO	Plant uptake compensation factor	0.45	0.6592

15	CH_K2	Effective hydraulic conductivity in main channel alluvium, mm hr^{-1}	0.31	0.7596
16	SOL_K	Saturated hydraulic conductivity, mm h^{-1}	0.25	0.8059
17	ESCO	Soil evaporation compensation factor	0.19	0.8491
18	GW_REVAP	Groundwater “revap” coefficient	0.06	0.9543
19	SOL_AWC	Available water capacity of the soil layer, mm H_2O mm $soil^{-1}$	0.02	0.9849

It can be observed in Table 5 that the most sensitive parameter for the Mundaú River Basin was the Curve Number for moisture condition II (CN2), followed by the deep aquifer percolation fraction (RCHRG_DP), the depth from soil surface to bottom of layer (SOL_Z), the Manning's "n" value for overland flow (OV_N), the maximum canopy storage (CANMX) and the lateral flow travel time (LAT_TTIME), respectively.

The CN2 had the highest t-Stat value, in absolute terms, with 4.28 and lower value of P-Value, with a value of 0.0004. The second most sensitive parameter considered by the automatic calibration, the RCHRG_DP, presented t-Stat in absolute terms of 3.38 and P-Value of 0.003. The third, fourth and fifth most sensitive parameters (SOL_Z, OV_N and CANMX) presented t-Stat values of 2.44, 2.35 and 1.92 and P-Value values of 0.0241, 0.029 and 0.0695, respectively. These parameters are related to processes such as surface runoff, groundwater flows, soil physics and crop development. Several studies have pointed these parameters as sensitive (Jha, 2009, Schmalz and Fohrer, 2009, Cibin et al., 2010, Santosh et al., 2010, Lelis et al., 2012, Bressiani, 2016).

3.4 Uncertainty analyses, calibration and validation

As a first step to the calibration, a phase of data collection should be performed, which comprise "soft" and "hard" data collection. "Soft" data include information on the qualitative knowledge of the modelers or from the scientific literature, such as reports, theses and dissertations about the basin studied or about another basin with similar characteristics. As an example of these data, there are averages of evapotranspiration, baseflow rate estimates, average depth of aquifers, average leaf area index and crop productivity. "Hard" data are the measured data, such as the time series of discharge, sediment, groundwater levels, monitored soil moisture, measured evapotranspiration, among others. These data are generally used for calibration (Bressiani, 2016). It is extremely important that not only hard data be used in the calibration, but that soft data is also incorporated into the process (Arnold et al., 2015, Gupta et al., 2014, Seibert and McDonnell, 2002).

The calibration procedure of SWAT model was performed semi automatically in the SWAT Calibration and Uncertainty Programs (SWAT-CUP) using the Sequential Uncertainty Fitting algorithm (SUFI-2). Additionally, the Nash-Sutcliffe (NS) coefficient was used as goal function. SUFI-2 is a routine used to capture the uncertainties of the modeling process. According to Abbaspour (2015), there is a close relationship between the calibration process and the uncertainties, and it is of great importance to identify them. In SUFI-2, the uncertainty of the input parameters is identified in the uniform distribution of the parameters, whereas the uncertainties of the output parameters are expressed from the 95 PPU (95% probability distribution), which are calculated at levels of 2.5% and 97.5% of the cumulative distribution of an output variable, using Latin American Hypercube Sampling. The quantification of the adjustment between the simulation results and the observed data, expressed as 95 PPU, can be performed by two statistical indices: The p-factor and the r-factor. The p-factor is the percentage of the observed data points within the uncertainty of model prediction, at 95 PPU, and varies from 0 to 1, where 1 indicates 100% adjustment of the measured data within model prediction uncertainty (i.e., a perfect model simulation considering the uncertainty); while the r-factor is the mean uncertainty of the 95 PPU. For this study we consider that values of the p-factor above 70% and values of the r-factor close to 1 are excellent for discharge data. In this study, we used the p-factor and the r-factor to analyze the uncertainties of hydrological simulation.

In studies that involve hydrological modeling through the use of streamflow data, it is necessary that the data series used for this modeling constitutes at least 15 years of extension, in order to identify important properties related to hydrological processes (Kennard et al., 2010). The SWAT model was applied for the period from 2000 to 2016 (17 years), in which the first three years (2000, 2001 and 2002) were used to warm up the SWAT model and were not considered in the modeling. The calibration (2003-2009) and validation (2010-2016) processes with discharge data occurred in a hierarchical way, first with an annual time step and then with a monthly time step, starting from the most upstream stations then proceeding to the closest station to the basin outlet, with a total of five stations calibrated and validated along the watershed. For soil moisture data, the model was calibrated and validated using daily soil moisture measurements, in the years of 2014 and 2015, respectively.

Some tests performed for the hierarchical calibration of the SWAT model have been proposed by Klemes (1986): Split-Sample Test, Differential Split-Sample Test and Proxy-Catchment Test. In this study, the Split-Sample Test was applied, which consists of a classic test, where the series of hydrological data should be divided into two segments; one for calibration and the other for validation. This division might occur in two equal parts (50/50) (when the series is sufficiently long), or in the configuration (70/30) (when the series is not sufficiently long), as is the case of this study (17 years of data). In the calibration and validation process of the SWAT model for the Mundaú River Basin, in each sub-basin studied, the data series used for calibration/validation varied among sub-basins, ranging from 50/50 to 78/22 and averaging approximately 70/30. The calibration data included both dry and wet periods.

There are several statistical performance indicators for hydrological simulation. The most commonly reported for SWAT calibration and validation are the coefficient of determination (R^2, Eq. 10), the Nash-Sutcliffe coefficient (NS, Eq. 11) and the percent bias (PBIAS, Eq. 12).

$$R^2 = \frac{\left[\sum_i (Q_{obs,i} - \bar{Q}_{obs})(Q_{sim,i} - \bar{Q}_{sim})\right]^2}{\sum_i (Q_{obs,i} - \bar{Q}_{obs})^2 \sum_i (Q_{sim,i} - \bar{Q}_{sim})^2} \tag{10}$$

$$NS = 1 - \frac{\sum_i (Q_{obs} - Q_{sim})_i^2}{\sum_i (Q_{obs,i} - \bar{Q}_{obs})^2} \tag{11}$$

$$PBIAS = 100 \frac{\sum_{i=1}^{n} (Q_{obs} - Q_{sim})_i}{\sum_{i=1}^{n} (Q_{obs,i})} \tag{12}$$

Where: Q_{obs} is the observed discharge; Q_{sim} is the simulated discharge; $\bar{Q}_{obs}$ is the mean observed discharge and $\bar{Q}_{sim}$ is the mean simulated discharge.

The NS varies between negative infinite and 1.0 (the optimal value). Values between 0 and 1 are generally regarded as acceptable performance levels and values ≤ 0 indicate that it is better to use the mean observed data than the predicted value of the model (Nash and Sutcliffe, 1970). In relation to PBIAS, its optimal value is 0, with low magnitudes indicating good precision in the simulation of the model. Positive values indicate underestimation by the model and negative values indicate overestimation (Gupta et al., 1999).

According to Abbaspour et al. (2004), a model is to be considered satisfactorily calibrated by SUFI-2 when R^2 is higher than 0.80. Moriasi et al. (2007) states NSE > 0.5 and -25% < PBIAS < 25% as satisfactory values, while NSE > 0.75 and -10% < PBIAS < 10% are considered very good for discharge calibration of hydrological models.

A general summary of processing with the SWAT model is shown in Figure 10. The processing involves basically 4 stages, including input data insertion (Step 1), project creation by associating the model with the Geographic Information System, and all steps required to run the model (Step 2), calibration, validation, sensitivity and uncertainty analyzes, which can be performed with the SWAT-CUP software (Step 3), and forecast scenarios creation using the calibrated model (Step 4).

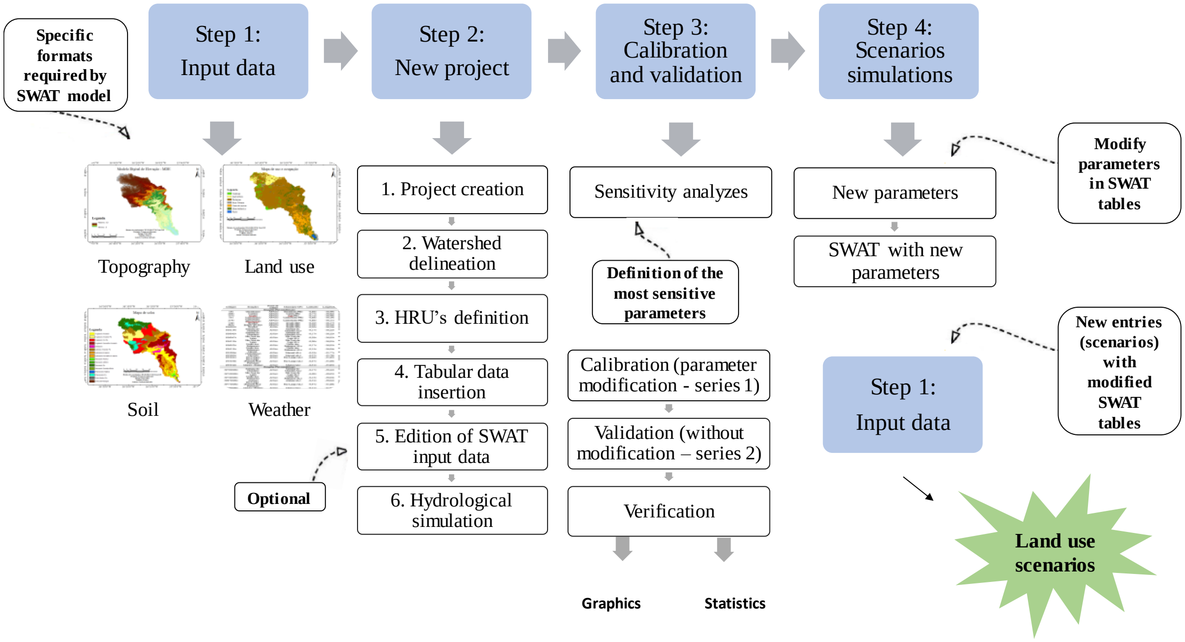


Fig. 10. Conceptual framework of SWAT model and its setup

References

Abbaspour, K.C., 2015. SWAT-CUP: SWAT Calibration and Uncertainty Programs - A User Manual. Eawag: Swiss Federal Institute of Aquatic Science and Technology. 100p.

Abbaspour, K.C., Johnson, C.A., Van Genuchten, M.T., 2004. Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure. Vadose Zone Journal, 3, 1340-1352. http://dx.doi.org/10.2136/vzj2004.1340.

Abbaspour, K.C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H., Klove, B., 2015. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. Journal of Hydrology, 524, 733–752. http://dx.doi.org/10.1016/j.jhydrol.2015.03.027.

Abbaspour, K.C., Yang, J., Maximov, I., Siber, R., Bogner, K., Mieleitner, J. Zobrist, J., Srinivasan, R., 2007. Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. Journal of Hydrology, 333, 413-430. http://doi.org/10.1016/j.jhydrol.2006.09.014.

Arnold, J.G., Kiniry, J.R., Srinivasan, R., Williams, J.R., Haney, E.B., Neitsch, S.L., 2012. Input/Output Documentation version 2012. Texas Water Resources Institute – TR-439. 650p.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment part I: model development. Journal of the American Water Resources Association, 34, 73-89. http://dx.doi.org/10.1111/j.1752-1688.1998.

Arnold, J.G., Youssef, M.A., Yen, H., White, M.J., Sheshukov, A.Y., Sadeghi, A.M., Moriasi, D.N., Steiner, J.L., Amatya, D.M., Skaggs, R.W., Haney, E.B., Jeong, J., Arabi, M., Gowda, P.H., 2015. Hydrological processes and model representation: impact of soft data on calibration. Transactions of the ASABE, 58, 6, 1637-1660. http://dx.doi.org/10.13031/trans.58.10726.

Blainski, E., Silveira, F.A., Conceição, G., Garbossa, L.H.P., Vianna, L.F., 2011. Simulação de cenários de uso do solo na bacia hidrográfica do rio Araranguá utilizando a técnica da modelagem hidrológica. Agropecuária Catarinense, 24, 1, 65-70.

Bressiani, D.A., 2016. Coping with hydrological risks through flooding risk index, complex watershed modeling, different calibration techniques, and ensemble streamflow forecasting. Thesis (Doctorade). São Carlos Engineering School – University of São Paulo. 192p.

Bressiani, D.A., Gassman, P.W., Fernandes, J.G., Garbossa, L.H.P., Srinivasan, R., Bonumá, N.B., Mendiondo, E.M., 2015. Review of Soil and Water Assessment Tool (SWAT) applications in Brazil: Challenges and prospects. International Journal of Agricultural and Biological Engineering, 8, 9-35. http://dx.doi.org/10.3965/j.ijabe.20150803.1765.

Cibin R., Sudheer, K. P., Chaubey, I., 2010. Sensitivity and identifiability of stream flow generation parameters of the SWAT model. Hydrological Processes, 24, 1133-1148. https://doi.org/10.1002/hyp.7568.

Cordero, A., 2013. Apostila de hidrologia. Centro de Ciências Tecnológicas – CCT – Universidade Regional de Blumenau – FURB. Blumenau. 108p.

Gassman, P.W., Sadeghi, A.M., Srinivasan, R., 2014. Applications of the SWAT model special section: overview and insights. Journal of environmental quality, 43, p.1-8. https://doi.org/10.2134/jeq2013.11.0466.

Green, W.H., Ampt, G.A., 1911. Studies on soil physics, 1. The flow of air and water through soils. Journal of Agricultural Sciences, 4, 1, 1-24. https://doi.org/10.1017/S0021859600001441.

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

Gupta, H.V., Sorooshian, S., Yapo, P.O., 1999. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. J. Hydrologic Eng., 4, 2, 135-143. https://doi.org/10.1061/(ASCE)1084-0699(1999)4:2(135).

Jha, M., 2009. hydrologic simulations of the Maquoketa River Watershed using SWAT. Available: http://ageconsearch.umn.edu/bitstream/51123/2/09-WP_492.Jha.pdf. Acessed: October 2016.

Kenard, M.J., Mackay, S.J., Pusey, B.J., Olden, J.D., Marsh, N., 2010. Quantifying uncertainty in estimation of hydrologic metrics for ecohydrological studies. River Research and Applications, 26, 2, 137-156. https://doi.org/10.1002/rra.1249.

Klemes, V., 1986. Operational testing of hydrological simulation models. Hydrological Sciences Journal, 31, 13-24. http://dx.doi.org/10.1080/02626668609491024.

Lelis, T. A., Calijuri, M. L., Santiago, A. F., Lima, D. C., Rocha, E. O., 2012. Análise de sensibilidade e calibração do modelo SWAT aplicado em bacia hidrográfica da região Sudeste do Brasil. Revista Brasileira de Ciência do Solo, 36, 623-634. http://dx.doi.org/10.1590/S0100-06832012000200031.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Binger, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE, 50, 3, 885-900. http://dx.doi.org/10.13031/2013.23153.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models: Part 1. A discussion of principles. Journal of Hydrology, 10, 282-290. http://dx.doi.org/10.1016/0022-1694(70)90255-6.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2005. Soil and water assessment tool: Theoretical documentation version 2005. Temple: Blackland Research Center, 541p.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. Soil and water assessment tool: Theoretical documentation version 2009. Temple: Blackland Research Center, 654p.

Obiero, J.P.O, 2013. Pedotransfer functions for saturated hydraulic conductivity for surface runoff modeling. Thesis (Doctorate). School of Engineering. University of Nairobi. 164p.

Paca, V.H.M., 2008. Análise de informações satelitais e dados convencionais da rede pluvio-fluviométrica como contribuição à modelagem hidrológica na região Amazônica - Estudo de caso: Bacia do rio Guamá – Pará. Dissertação (Mestrado). Universidade Federal do Rio de Janeiro. Rio de Janeiro. 135p.

Pereira, D.R., 2013. Simulação hidrológica na Bacia Hidrográfica do Rio Pomba usando o modelo SWAT. Tese (Doutorado em Engenharia Agrícola). Universidade Federal de Viçosa: Minas Gerais/MG. 142p.

Pinto, D.B.F., 2011. Aplicação do modelo SWAT (Soil and Water Assessment Tool) na simulação hidrossedimentológica em Bacia Hidrográfica da Serra da Mantiqueira, MG. Tese (Doutorado em Engenharia Agrícola). Universidade Federal de Lavras: Lavras/MG. 224p.

Pruski, F.F., Brandão, V.S., Silva, D.D., 2008. Escoamento superficial. 2ed. Editora UFV. Universidade Federal de Viçosa – Viçosa: UFV. 87p.

Rallison, R.E., Miller, N., 1981. Past, present and future SCS runoff procedure. In V.P. Singh (ed.). Rainfall runoff relationship. Water Resources Publication, 353-364.

Santosh, T., Kolladi, R., Surya, T., 2010. Influence of scale on SWAT model calibration for streamflow in a river basin in the humid tropics. Water Resources Management, 24, 4567-4578. http://dx.doi.org/10.1590/S0100-06832012000200031.

Saxton K.E., Rawls, W.J., 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Science Society of Agronomy Journal, 70, 5, 1569-1578.

Schmalz, B., Fohrer, N., 2009. Comparing model sensitivities of different landscapes using the ecohydrological SWAT model. Advances in Geosciences, 21, 91-98. https://doi.org/10.5194/adgeo-21-91-2009.

Seibert, J., McDonnell, J.J., 2002. On the dialog between experimentalist and modeler in catchment hydrology: Use of soft data for multicriteria model calibration. Water Resources Research, 38, 11, 1-14. https://doi.org/10.1029/2001WR000978.

Shepard, D., 1968. A two-dimensional interpolation function for irregularly-spaced data. In: ACM. Proceedings of the 1968 23rd ACM national conference, 517-524.

Silva, A.S.A., 2015. Ferramentas para modelagem e interpolação de dados ambientais em escala regional. Tese (Doutorado). Universidade Federal Rural de Pernambuco - UFRPE. Recife, PE. 107p.

Sloan, P.G., Morre, I.D., Coltharp, G.B., Eigel, J.D., 1983. Modeling surface and subsurface stormflow on steeply-sloping forested watersheds. Water Resources Inst. Report 142. Univ. Kentucky, Lexington.

Soil Conservation Service., 1972. Section 4: Hydrology In National Engineering Handbook. SCS.

Strauch, M., Bernhofer, C., Koide, S., Volk, M., Lorz, C., Makeschin, F., 2012. Using precipitation data ensemble for uncertainty analysis in SWAT streamflow simulation. Journal of Hydrology, 414–415, 413–424. https://doi.org/10.1016/j.jhydrol.2011.11.014.

Strauch, M., Volk, M., 2013. SWAT plant growth modification for improved modeling of perennial vegetation in the tropics. Ecological Modelling, 269, 98-112. http://dx.doi.org/10.1016/j.ecolmodel.2013.08.013.

Thiessen, A.H., 1911. Precipitation averages for large areas. Monthly weather review, 39, 7, 1082-1089.

Tucci, C.E.M., 2013. Hidrologia: ciência e aplicação. 4. Ed. Porto Alegre: Editora da UFRGS/ABRH. 943p.

4. *Soil moisture and discharge modeling in a representative watershed in northeastern Brazil using SWAT*

This chapter was accepted to an international journal, with the following co-authors: Andrade, C.W.L., Montenegro, S.M.G.L., Montenegro A.A.A., Lima, J.R.S., Srinivasan, R. and Jones, C.A.

Abstract

Soil moisture and discharge are interrelated variables which play a major role on water availability, environmental conservation and ecohydrological functioning of a watershed. In order to investigate their spatio-temporal dynamics, hydrological models are valuable tools. However, to minimize uncertainties of the modeled estimates, good quality distributed observational data sets are required for realist predictions. The aim of this study is to apply the Soil and Water Assessment Tool (SWAT) in a representative watershed of the northeastern Brazil, and to evaluate the effects of using both discharge and soil moisture datasets on the model uncertainties and predictions. The study area is located in the Mundaú River Basin (4,090.39 km²), situated in the States of Pernambuco and Alagoas, in Brazil. Considering two variables and five streamflow gauge stations, different calibration strategies were evaluated, through the Split-Sample Test, in annual, monthly and daily time steps. For streamflow, the values of the Nash-Sutcliffe model efficiency (NS) among gauge stations ranged from 0.71 to 0.92 in the calibration phase for the annual time step, and between 0.55 and 0.78 in the monthly time step. In the validation phase, NS values ranged from 0.53 to 0.76 for the annual time step, and between 0.62 and 0.72 for the monthly time step. Calibration and validation against daily soil moisture data resulted in a NS values of 0.53 and 0.52, and PBIAS of 0.4% and -1.1%, respectively. These results represent "satisfactory" and "very good" performances for discharge and soil moisture. Although there is still some amount of uncertainty, the use of complementary data, such as soil moisture, to calibrate and validate the SWAT model is useful, especially when discharge data are scarce, as for some watersheds in the semiarid zone.

Keywords: Data scarcity, Soil moisture, Hydrological modeling, SWAT-CUP, Uncertainty analysis

4.1 Introduction

Increasing water scarcity and the lack of water resources planning and management are major tasks for meeting future water demands and reducing society vulnerability (ONU, 2012). According to Marengo (2014), drought events might affect water and economic security in Brazil, generating restrictions on the water supply for the population and for the environmental sustainability.

Hydrological models provide an overall understanding of processes dynamics that occur in the soil-plant-atmosphere system, although presenting a degree of uncertainty in their results (Engel et al., 2007). Increasingly, such tools have been used for planning, management and water resources policy. For consistent predictions, uncertainties inherent to the model calibration, validation and evaluation should be accounted for (Harmel and Smith, 2007).

Studies related to the analysis of uncertainties of distributed models have been increasing carried out (Abbaspour et al., 2018). According to Abbaspour (2015), calibration and analysis of uncertainties of semi-distributed watershed models are subject to a number of issues, such as their parameterization, the non-uniqueness of a set of parameters, the definition of what is a "calibrated model", what are the appropriate limits of its use, and the calibration in watersheds where land uses or streams have been greatly modified. In addition, input data and spatial scale simplifications are also considered as sources of uncertainties (Abbott and Refsgaard, 1996; Beven, 2012).

In direct modeling, calibration with a single parameter value results in a single model signal. On the other hand, in an inverse modeling, the observed data can be well estimated by different sets of parameters; that is, with different solutions (Abbaspour, 2015). Inverse modeling has become a widely used calibration method in recent years (Andrade et al., 2013; Abbaspour et al., 2015; Bressiani et al., 2015; Franco and Bonumá, 2017; Blainski et al., 2017). The approach that considers more than a single variable to calibrate and validate the model can help reduce the uncertainties associated to calibration procedure (Beven, 2006, 2012; Dagguppati et al., 2015). Additionally, the adoption of different streamflow gauge stations along the watershed might also reduce uncertainties.

Among the various distributed hydrologic models, the Soil and Water Assessment Tool (SWAT), a semi-distributed, continuous-time, process based hydrology and water quality model (Neitsch et al., 2011), was developed to analyze the impacts of land use changes on discharge, erosion, sedimentation, and water quality in gauged and ungauged watersheds (Arnold et al., 1998). It is an open source code that considers different hydrologic and agronomic processes, ranging from catchment to continental scales (Abbaspour et al., 2015; Bressiani et al., 2015).

Soil moisture plays an important role in the hydrology of a watershed, affecting several hydrological processes and characteristics, such as infiltration, percolation, hydraulic conductivity, recharge and discharge. However, there are still a reduced number of studies involving the calibration of distributed hydrological models, such as SWAT, based on measurements of soil moisture, despite its potential in reducing modeling uncertainties in data-scarce situations. Rajib et al. (2016) performed a multi-objective calibration of the SWAT model using spatially distributed remotely sensed and in situ soil moisture, along with streamflow observations. According to the authors, acceptable streamflow simulation can be obtained without using any soil moisture information in model calibration. However, although there is considerable amount of uncertainty/equifinality, the use of soil moisture data improved the simulated results. Li et al. (2018) performed the SWAT model calibration using streamflow measurements and remote sensing derived soil moisture values and a more consistent and statistically significant improvement was achieved due to the spatial information introduced by the remotely sensed soil moisture data.

The aim of this study is to apply the Soil and Water Assessment Tool (SWAT) in a representative watershed of the northeastern Brazil, and to evaluate the effects of using two observational datasets on the model uncertainties and predictions. For the SWAT model calibration and validation in this data-scarce region, we investigate the use of two variables, namely the experimental soil moisture data from sensors and the observed discharge obtained from five streamflow gauging stations along the watershed.

4.2 Material and Methods

4.2.1 Study area

The Mundaú River Basin (MRB) has a drainage area of 4,090.39 km², spreading throughout the States of Pernambuco and Alagoas, in northeastern Brazil (Fig. 1). The MRB is predominantly rural, has substantial agricultural activity, including a large dairy and broilers breeding industry. It also has substantial sugarcane production and processing industry. The basin has urban areas, covering 34 municipalities, composed by native vegetation (comprised of a small region of Caatinga, and areas of Atlantic Forest), water bodies, such as the Mundaú River Lagoon, and large pasture areas (Andrade et al., 2017b). The Caatinga vegetation is characterized by seasonally dry shrubs and forests (Leal et al., 2005), while the Atlantic Forest vegetation exhibits seasonally dry and tropical forests (Werneck, 2011). Mangroves and coastal vegetation are also found in the region.

The climate, according to the Köppen classification, is Aw (Tropical, with dry season in winter). Most of the MRB is classified, in relation to amount of rainfall, as semi-humid and a small portion classified as semiarid, with an average temperature of 24 ºC. The average annual rainfall in the MRB is 800 mm (Alvares et al., 2014), ranging from 497 to 1.143.63 mm (Araújo et al., 2015), with precipitation declining as the distance from the coast increases.

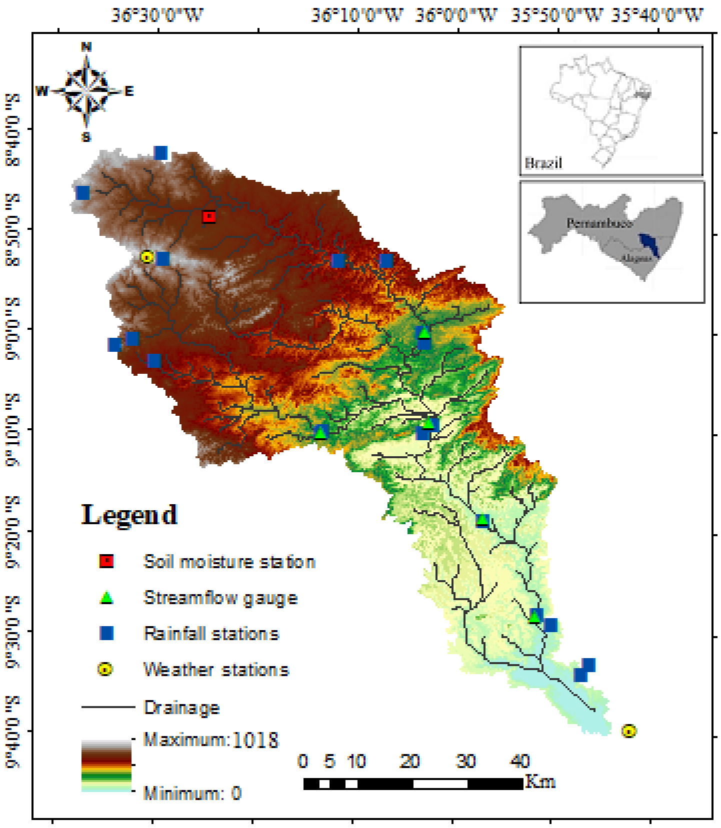


Fig. 1. Location map of Mundaú Watershed showing soil moisture, streamflow and weather stations

4.2.2 Soil and Water Assessment Tool (SWAT) model and input data

Soil and Water Assessment Tool (SWAT) model, freely available at (http://swat.tamu.edu/) is a semi-conceptual, semi-distributed, continuous-time, process based hydrology and water quality model that uses a daily time step and multiple hydrologic units to simulate different physical processes within the study area, as such as climate, hydrology (surface runoff, percolation, interception, infiltration, subsurface flow, baseflow and evapotranspiration), soil moisture, plant growth, nutrients, pesticides, bacteria and pathogens, and soil management (Arnold et al., 2012a).

For the hydrological modeling with SWAT, the watershed is previously divided into several sub-basins, which amount depends on the minimum drainage area. Afterwards, the model carries out combinations among the land use, soil types and slope layers, producing the Hydrological Response Units (HRUs). Evapotranspiration estimation, as well as surface runoff, is predicted separately for each HRU, to enable a better physical representation of hydrological processes (STRAUCH et al., 2012).

The SWAT model offers three options for estimating the potential evapotranspiration (ET0) component: Penman-Monteith-FAO, Hargreaves & Samani and Priestley-Taylor methods. The model standard method is the Penman-Monteith-FAO, which requires meteorological variables such as solar radiation, temperature, relative humidity and wind speed (Neitsch et al., 2005). In the present study, the Hargreaves & Samani method was adopted, as it requires only radiation and temperature data, and it fits very well for semiarid regions.

The SWAT model requires four main types of input data, including three maps, which are the digital elevation model (DEM), the land use map, the soil type map, and a series of meteorological data, such as: precipitation, maximum and minimum air temperatures, relative humidity, wind speed and solar radiation. Table 1 presents the sources used for the Mundaú Basin, related to maps, hydrological and meteorological data sources as well as the data description used with the SWAT model.

Table 1. Sources of data used in hydrological modeling with SWAT, for the Mundaú Basin

Description	Data description	Institution/ Agency
Digital Elevation Model (DEM)	Spatial (resolution: 90 m)	EMBRAPA (SRTM)
Land use map	Spatial	INPE, MMA, CONAB, IBGE
Soil type map	Spatial (scale: 1: 100,000)	EMBRAPA (ZAPE and ZAAL), scientific articles
Weather stations	Daily data series	ANA, APAC and INMET
Discharge data*	Annual/ monthly data series	ANA
Soil moisture data*	Daily data series	Experimental data from UFRPE
Digital Elevation Model (DEM)	Spatial (resolution: 90 m)	EMBRAPA (SRTM)

INPE - National Institute of Space Research, MMA - Ministry of the Environment, CONAB - National Supply Company, IBGE - Brazilian Institute of Geography and Statistics, EMBRAPA - Brazilian Agricultural Research Corporation, ZAPE - Agroecological Zoning of Pernambuco, ZAAL - Agroecological Zoning of Alagoas, SRTM - Shuttle Radar Topography Mission, ANA - National Water Agency, APAC - Pernambuco State Agency for Water and Climate, INMET - National Institute of Meteorology, UFRPE - Federal Rural University of Pernambuco. *Data for the SWAT model calibration and validation.

The digital elevation model (DEM) was obtained from the Brazilian Agricultural Research Corporation – EMBRAPA (Figure 1). The land use map of the MRB was constructed using satellite images and image processing tools from LANDSAT 5. The images interpretation was carried out through digital processing tools associated with GPS data collection. Mapping was performed using the supervised classification method, adopting the maximum likelihood classifier. Land use was divided into seven classes, presented in Figure 2A. The association of land uses defined in the MRB with the land use classes in the SWAT database are presented in Table 2. The sixteen soil classes present in the MRB are show in Figure 2B.

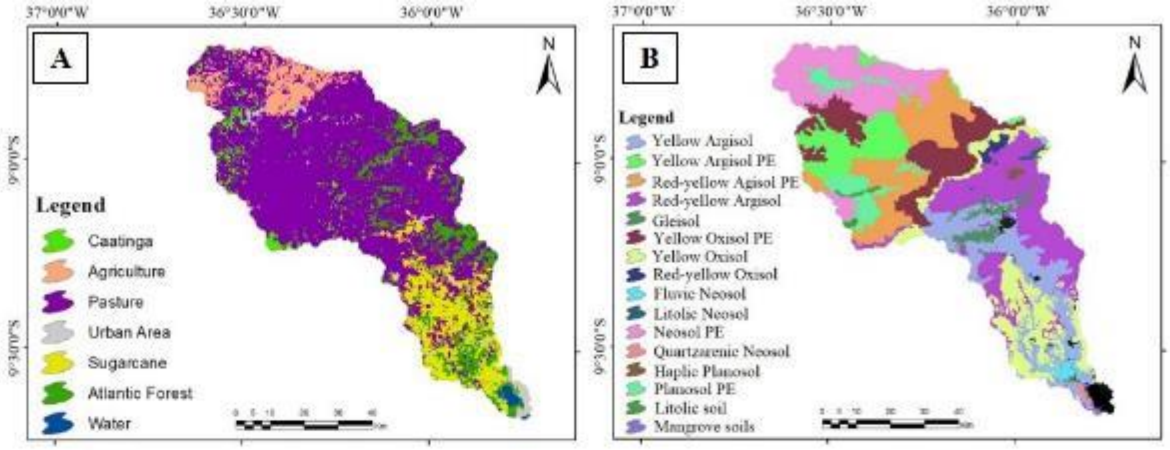


Fig. 2. Land use map (A) and soil types map (B) of the Mundaú Basin

Table 2. Association of existing land uses in the study with existing uses in the SWAT database for the MRB

Class	Land use	Area (%)	SWAT database class
i	Pasture	67.0	Pasture (PAST)
ii	Agriculture	6.4	Agricultural Land-Generic (AGRL)
iii	Caatinga	2.9	Range Brush (RNGB)
iv	Atlantic Forest	10.9	Forest Evergreen (FRSE)
v	Sugarcane	11.2	Sugarcane (SUGC)
vi	Urban area	1.2	Residential (URBN)
vii	Water	0.4	Water (WATR)

In relation to the weather stations, eleven stations measuring only precipitation and two stations recording other meteorological data were adopted. Additionally, five streamflow gauge stations and one soil moisture station were selected for this study. The stations locations are presented in Figure 1.

One of the major problems in modeling Brazilian River basins is the lack of extensive series of hydro-meteorological data (high number of failures) or when the data are present, they often lack consistency. Regarding the data availability for the Mundaú River basin, there are rainfall data since the 1920s; however, such data present large numbers of failures and not all stations distributed along the watershed have the same data recording period. Therefore, a detailed survey was carried out on all the stations, aiming to examining their failures and consistencies, until verifying that the period of rainfall data considered acceptable for hydrological modeling with the SWAT model for the MRB is from 2000 to 2016, constituting 17 years of observational data.

In relation to streamflow data, although there are data since 1980, due to accentuated failures in older periods, the adopted experimental period was from 2000 to 2016, comprising 17 years, which is usually enough to capture long term time variations, as stated by Kennard et al. (2010). These authors point out that in studies that involve hydrological modeling through the use of streamflow data, it is recommended that the data series used for modeling presents at least 15 years of records, in order to allow identification of important properties related to hydrological processes variability and dynamics.

The experimental soil moisture data (m3 m-3) were obtained from sensors (Campbell Scientific – CS 616), installed at the soil profile every 10 cm up to 50 cm depth, and connected to an agrometeorological station located in a strategic area of the watershed, under supervision of the Federal Rural University of Pernambuco – Garanhuns Academic Unit, that provide soil moisture data recorded every 30 minutes. The station is located at Fazenda Riacho do Papagaio, municipality of São João - PE (8º 48' 34.2" S and 36º 24' 29.2" W, 695 m), with an area of 16 ha of pasture (Figure 1). Soil water content (mm) was calculated from soil moisture (m^3 m-^{3}), considering a depth of 50 cm and the measurements were extrapolated to the sub-basin at which the station is located. There are soil moisture records since 2011 in the station, representing a time series of 7 years. For the purpose of this study, only two years of data was adopted, due to higher data quality for this period. Such configuration presented previously shows that the "date scarcity" condition is an important issue for the Mundaú River basin.

4.2.3 Calibration and validation procedures

The calibration procedure of SWAT model was performed in the SWAT Calibration and Uncertainty Programs (SWAT-CUP). The SWATCUP is an independent software developed for sensitivity analyses, calibration and validation, and uncertainty analyses based on SWAT simulations. The program comprises five calibration procedures (SUFI-2, PSO, GLUE, ParaSol and MCMC), eleven goal functions (mult, sum, R2, chi2, NS, br2, ssqr, PBIAS, KGE, RSR, MNS) and includes applications such as visualization of the study area (Abbaspour et al., 2018). In this study, the calibration procedure was performed in the SWAT-CUP using the Sequential Uncertainty Fitting algorithm (SUFI-2). Additionally, the Nash-Sutcliffe model efficiency (NS) coefficient was used as goal function.

SUFI-2 is a routine used to capture the uncertainties of the modeling process. According to Abbaspour (2015), there is a close relationship between the calibration process and the uncertainties, and it is of great importance to identify them. In SUFI-2, the uncertainty of the input parameters is expressed as ranges, whereas the uncertainties of the output parameters are expressed from the 95 PPU (95% probability distribution), which are calculated at levels of 2.5% and 97.5% of the cumulative distribution of an output variable, using Latin American Hypercube Sampling. The quantification of the adjustment between the simulation results and the observed data, expressed as 95 PPU, can be performed by two statistical indices: The p-factor and the r-factor. The p-factor is the percentage of the observed data points within the uncertainty of model prediction, at 95 PPU, and varies from 0 to 1, where 1 indicates 100% adjustment of the measured data within model prediction uncertainty (i.e., a perfect model simulation considering the uncertainty); while the r-factor is the mean uncertainty of the 95 PPU. For this study, values of the p-factor above 70% and values of the r-factor close to 1 were considered as adequate for discharge simulations. In this study, the p-factor and the r-factor were adopted to analyze the uncertainties of hydrological simulation.

The sensitivity analysis used in this study was previously performed by Andrade et al. (2017a), using the SUFI-2 of the SWAT-CUP, considering a global sensitivity analysis of 19 parameters related to the processes of flow, evapotranspiration, percolation, recharge, infiltration, among others, in order to identify the most sensitive ones for the MRB simulations. According to the authors, the two most sensitivity parameters were the Curve Number for moisture condition II (CN2) and the coefficient of water percolation to the deep aquifer (RCHRG_DP). The CN2 was one of the parameters chosen for the calibration of the present study. In addition, some other parameters were analyzed, which did not present such sensitivity in the previous study of Andrade et. al (2017a). The fact is that the latter authors worked with only part of the MRB while the present study focuses on the whole basin. Such difference in scale interferes in the sensitivity analysis, that is, the seven parameters used for calibration in this study are not necessarily the same proposed by Andrade et al. (2017a).

The first three years of the available streamflow data series were used to warm up the SWAT model (2000-2002). The calibration (2003-2009) and validation (2010-2016) processes occurred in a hierarchical way, first with an annual time step and then with a monthly time step, starting from the most upstream stations then proceeding to the closest station to the basin outlet, with a total of five stations calibrated and validated along the watershed. Several researchers used time series of streamflow data with less than 17 years to calibrate and validate the SWAT model, such as Wallace et al. (2018), which worked with 8 years of data, Tuo et al. (2016) which used 10 years of discharge data, and Narsimlu et al. (2015) which adopted 16 years of fluviometric data for SWAT modeling. For soil moisture data, the model was calibrated and validated using daily soil moisture measurements, for the years of 2014 and 2015, respectively.

Some tests performed for the hierarchical calibration of the SWAT model have been proposed by Klemes (1986): Split-Sample Test, Differential Split-Sample Test and Proxy-Catchment Test. In this study, the Split-Sample Test was applied, which consists of a classic test, where the series of hydrological data should be divided into two segments; one for calibration and the other for validation. This division might occur in two equal parts (50/50) (when the series is sufficiently long), or in the configuration (70/30) (when the series is not sufficiently long), as is the case of this study (17 years of data). In the calibration and validation process of the SWAT model for the Mundaú River Basin, in each sub-basin studied, the data series used for calibration/validation varied among sub-basins, ranging from

50/50 to 78/22 and averaging approximately 70/30. The calibration data included both dry and wet periods.

There are several statistical performance indicators for hydrological simulation. The most commonly reported for SWAT calibration and validation are the determination coefficient (R2), the Nash-Sutcliffe model efficiency (NS) and the percent bias (PBIAS). The NS varies between negative infinite and 1.0 (the optimal value). Values between 0 and 1 are generally regarded as acceptable performance levels and values ≤ 0 indicate that it is better to use the mean observed data than the predicted value of the model (Nash and Sutcliffe, 1970). In relation to PBIAS, its optimal value is 0, with low magnitudes indicating good precision in the model simulation. Positive values indicate underestimation by the model and negative values indicate overestimation (Gupta et al., 1999). According to Abbaspour et al. (2004), a model is to be considered satisfactorily calibrated by SUFI-2 when R2 is higher than 0.80. Moriasi et al. (2007) state NSE > 0.5 and -25% < PBIAS < 25% as satisfactory values, while NSE > 0.75 and -10% < PBIAS < 10% are considered very good for discharge calibration of hydrological models. In this study the statistical evaluation rating criteria used is based on Moriasi (2007).

In addition to the statistical evaluation, analyses were carried out on information frequently extracted from the hydrograph, especially some associated with the flow duration curves.

4.3 Results and Discussion

4.3.1 Optimized parameters for streamflow and soil moisture

Table 3 lists the parameters which were used for both discharge and soil moisture calibration in the annual, monthly, and daily time steps using the SWAT model, their descriptions within the model and their calibrated values.Those parameters are related to hydrological processes, such as Curve Number, moisture condition II (CN2); main channel manning’s coefficient (CH_N2); water depth in shallow aquifer required for return flow

(GWQMN); groundwater delay (GW_DELAY); baseflow recession constant (ALPHA_BF); saturated hydraulic conductivity (SOL_K) and available water capacity (SOL_AWC). According to Blainski et al. (2017), some of these parameters are difficult to measure, such as GWQMN, ALPHA_BF, and GW_DELAY. The adjusted values for the parameters were then adopted for validation, and scenarios generation. It is important to highlight that during the parameterization of a hydrological model for calibration, different intervals can produce good statistical results. However, these differences in values might result in incorrect responses to the prediction of land use and climate change scenarios, for example. Therefore, it is very important to know the basin characteristics in order to minimize the uncertainties related to parameterization (Schaefli et al., 2004; Zhang et al., 2009).

In the present study, the calibrated value of the curve-number (CN) parameter was 73.7. In rural basins, this value represents land use of normal permanent fields (as pastures) for hydrological group C, that is, soils capable of generating above average discharge and low infiltration rates. It was also noticed that these soil types present a considerable amount of clay and are usually shallow. Most of the soils present in the Mundaú River Basin have a type D hydrological group. However, there is also a large representation of group C, indicating that the value of the calibrated CN adequately represents the general characteristics of the watershed. Additionally, most of the basin is occupied by pastures, further confirming the adequate representation of this parameter in the studied area. Zettam et al. (2017), performing hydrological and sedimentological modeling in the Tafna river basin, Africa (a semiarid watershed with 7,245 km² of drainage area), found calibrated values of CN between 38.5 and 94. The catchment area of the Tafna river has 10 land uses types, dominated by calcaire soils, being the most part of the area characterized by pasture, Southwestern Range (SWRN) (perennial semiarid vegetation with leaf area index up 1.5), tomato and winter weat. Hammouri et al. (2017) assessed the impacts of climate change on water resources in arid and semiarid regions of Jordan, and found a calibrated value of CN equal to 82.6. The basin studied by the authors has about 60% of rainfed agricultural lands, and 20% are irrigated, with silty clay and silty clay loam as dominant soil types. Brouziyne et al. (2017), performing the manual calibration of the SWAT model in a semiarid watershed in North-western Morocco, found CN values between 58 and 70. Among the land use categories established by the authors, the main land cover class is the pasture, with approximately 42%, and large variability of soil types, ranging from loamy-clay soils to well-drained sandy soils. As expected, and highlighted by Lin et al. (2014), the spatial heterogeneity of land use and soil types has significant influence on the runoff spatial distribution in a catchment, and hence on the CN values.

Table 3. Parameters used in SWAT calibration and calibrated values (Rio Largo station)

Nº	Parameter	Description	Initial Range (Method)	Calibrated value
1	CN2	Curve Number, moisture condition II	69.8 – 93.0 (v)	73.7
2	ALPHA_BF	Baseflow recession constant, days	0 – 0.048 (v)	0.05
3	GWQMN	Depth of water in shallow aquifer required for return flow, mm	0 – 4,000 (v)	2,686.52
4	GW_DELAY	Groundwater delay, days	31 – 300 (v)	134.74
5	CH_N2	Manning's "n" value for the main channel	0.01 – 0.25 (v)	0.34
6	SOL_K	Saturated hydraulic conductivity, mm h^{-1}	0 – 1000 (v)	953.59
7	SOL_AWC	Available soil moisture capacity, mm mm^{-1}	-0.6 – 0.6 (r)	0.32

v – replace: replaces the existing value and r – relative: multiplies the existing value

The baseflow recession constant (ALPHA_BF) ranged from 0 to 1 day, as suggested by Arnold et al. (2012a), with 0.05 being the calibrated value, very close to 0.048, which is the model default value. The interval chosen was the same as that adopted by Bressiani (2016), who worked with a watershed located in the Ceará State, northeastern Brazil, which has a predominantly Caatinga biome and is inserted in a predominantly semiarid climatic zone. According to Arnold et al. (2012a), ALPHA_BF values between 0.1 and 0.3 mean that there is a slow recharge response in the basin, while values between 0.9 and 1 indicate a rapid response. The fitted value of 0.05 indicates that the baseflow recession for the basin studied occurs slowly and consistently, which is expected for basins with perennial rivers, as is the case of the MRB. Pereira et al. (2014) found a calibrated ALPHA_BF value of 0.004 when performing hydrological simulation using the SWAT model in a headwater basin in Southeastern Brazil. Vaghefi et al. (2014) analyzed the impact of climate change on water resources components in semiarid regions of the Iran, found ALPHA_BF values ranging from 0 to 0.511. Using spatially distributed streamflow and remotely sensed soil moisture data, Rajib et al. (2016) performed the multi-objective calibration of the SWAT model, and found ALPHA_BF values ranging from 0.45 to 0.77 in the studied basins. Fontes Júnior (2016), performing experimentation and hydrological modeling in a semiarid Northeastern basin of Brazil, found a calibrated ALPHA_BF value of 0.063. Fukunaga et al. (2017), applying the SWAT model in the Itapemirim River basin (Brazil), a tropical catchment, found a calibrated ALPHA_BF value of 0.027.

The depth of water in shallow aquifers required for return flow (GWQMN) can vary from 0 to 4,000 mm, with these values being the default limits given by the SWAT model. The calibrated value of 2,686 mm indicates that for the occurrence of the return flow in the Mundaú Watershed, the water table should be equal to or greater than approximately 2.7 m in depth. The return flow from groundwater is related to rainfall and especially with evapotranspiration, since it is strongly dependent of capillary flow. Vaghefi et al. (2014) found GWQMN of 3,064.7 mm for a basin with precipitations of 240 to 660 mm year^{-1} and evapotranspiration ranging from 200 to over 1000 mm year^{-1}. Zhang et al. (2015), performing simulation of peak flows under climate change in Lanjiang catchment, East China, found GWQMN values from 2,465.11 mm to 4,673.13 mm. The catchment is characterized by a sub-tropical humid monsoon climate and the annual mean rainfall is about 1600 mm. Brighenti et al. (2016), when performing a hierarchical calibration of the SWAT model in a watershed in the Santa Catarina State, Brazil, found GWQMN of 2,290.54 mm. This basin presents similarities with the Mundaú River Watershed, such as the presence of Gleisols and maximum and minimum precipitation of 2,500 and 1,082 mm, respectively (as already stated, for Mundáu Basin rainfall varies from 497 to 1,143.63 mm). Some authors have found low values of GWQMN, particularly for catchments presenting shallow soils, as Fontes Júnior (2016), for the Alto Ipanema Basin (Brazil), with GWQMN of 717.5 mm, and Blainski et al. (2017), for Camboriú River Basin (Brazil), with GWQMN of 1,000 mm.

The groundwater delay (GW_DELAY) in the Mundaú River Basin (with 4,090.39 km²) was of approximately 135 days, whereas Xue et al. (2014), when analyzing the parameter uncertainty of surface flow and sediment yield in the Huolin Basin, China (with an area of 8,102 km²), found calibrated values of the GW_DELAY of 101 days. On the other hand, Blainski et al. (2017) found a value of 0.65, indicating that the time interval required for the underground recharge in the Camboriú River Basin (with 195 km^2) was less than 1 day. Such differences highlight the strong role of the drainage area size on the GW_DELAY parameter.

The Manning's "n" value for the main channel (CH_N2) calibrated in the present study was 0.34. Similarly to the ALPHA_BF, the CH_N2 is within the limit of the suggested range in SWAT input/ output document (Arnold et al., 2012a), which is $-0.01 < CH\_N2 < 0.3$. In this case, CH_N2 is in the maximum allowed value (CH_N2 = 0.34, approximately 0.3). Chow (1959) has a wide list of Manning's roughness coefficients for natural river channels and, according to the author, the main characteristics of channel with maximum values of CH_N2 (0.15) are very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush. Rajib et al. (2016) found values adjusted from 0.02 to 0.15 in the studied basins. In turn, Pereira et al. (2014) obtained 0.011 for the Galo Creek Watershed, located in the Espírito Santo State, Brazil. In the basin, Atlantic Forest vegetation and pasture correspond to approximately 53% and 42% of the area, respectively, and the soil is characterized as Red-Yellow Oxisols, which covers 92% of the area. Fontes Júnior (2016) found adjusted values from 0.072 to 0.254 in the studied basin, for water channels along alluvial deposits, and shrubs riparian vegetation alongside the river beds.

It can be seen in Table 3 that the calibrated value of the SOL_K parameter is very close to the upper limit allowed by the initial range (SOL_K = 953.59). According to Andrade et al. (2013), saturated hydraulic conductivity usually presents a high spatial variability, and the SWAT model does not take into account this spatial distribution but, rather, a mean value for a given soil type. Then, the model provides, from the optimization process, the maximum value allowed in the calibration step. Oliveira Júnior et al. (2014) obtained experimentally, in the same area of the present study, maximum values of SOL_K of 1036.8 and 1681.2 mm h^{-1} for pasture and Caatinga covers, respectively.

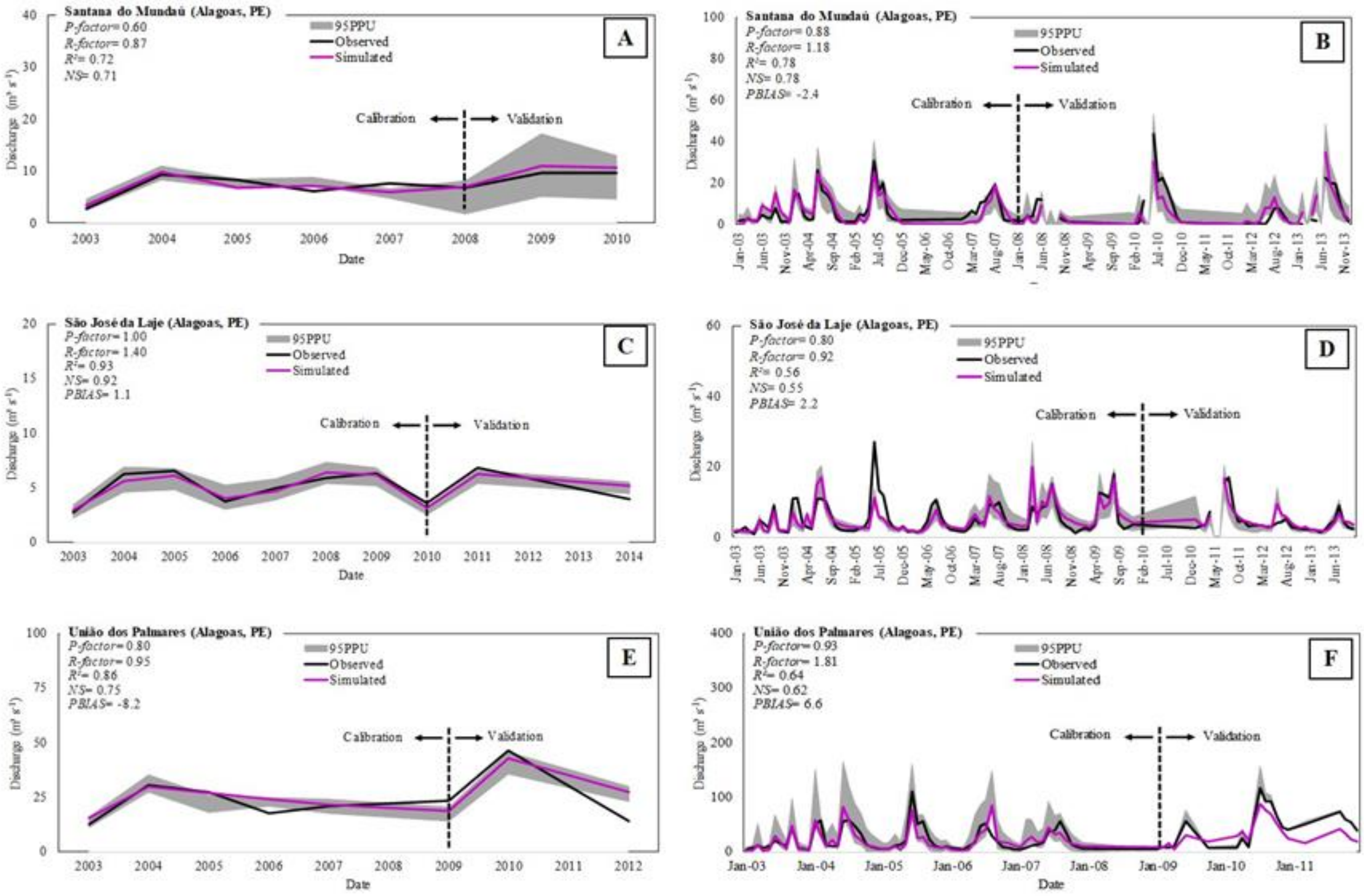
Initial estimates of available water capacity vary for different soil types, ranging from 0.04 mm mm-1 to 0.12 mm mm^{-1}. For SOL_AWC calibration, values were allowed to vary by a factor of -60% to +60%. Calibration resulted in a 32% increase in SOL_AWC for all soils, generating calibrated values between 0.053 mm mm^{-1} and 0.158 mm mm^{-1}.

4.3.2 Calibration and uncertainty analysis for streamflow

Comparison between the simulated and observed hydrographs is an important procedure to evaluate model calibration (Andrade et al., 2013; Blainski et al., 2017). Figures 3A through 3J show the hydrographs observed and simulated by the SWAT model, in the calibration and validation phases, for the five streamflow gauge stations of the Mundaú River Basin (Santana do Mundaú, São José da Laje, União dos Palmares, Murici and Rio Largo) for annual and monthly time steps, respectively. For both time steps, a satisfactory fitting between measured and simulated hydrograms was observed.

In general, good calibrations and validations are achieved when the data series used to calibrate and validate the model included both dry and wet years within the region. In addition, good correspondence between other model outputs and measured data (soil moisture, evapotranspiration, etc.) might increase confidence in model calibration (Arnold et al., 2012b; Zhang et al., 2015).

Good correspondence was observed (Figure 3) between the majority of simulated and measured peak flows, especially when the calibration and validation were performed in an annual time step. Andrade et al. (2017b), with the model still uncalibrated, had already observed good correspondences between the hydrographs simulated by SWAT and the data observed for the same study area. Observing the monthly hydrographs, some peaks were not well represented by the calibrated model, for example during 2003 at Santana do Mundaú (Figure 3B), when the model slightly overestimated the observed values. The same could be seen during validation in 2010, with the model underestimating the observed values. In 2012 there was a small displacement of the hydrograph to the left. At the São José da Laje Station, some differences between observed and simulated data could also be seen. For example, for calibration in the years of 2004 and 2005, when the model failed to reach the peak flows, causing the NS to decrease in relation to the other stations (Figure 3D). Although minimal, according to Silva and Medeiros (2014), these differences may be associated with model simulation difficulties or uncertainties in the input data. However, in general terms, the correspondence between observed and simulated flows were good in the MRB. The recession periods were well simulated by the SWAT model, under all proposed conditions, confirming the adequate representation and applicability of the SWAT model for the studied region. According to Andrade et al. (2013), the SWAT model fitting during the recession periods, both in calibration and validation periods, indicates good model performance in simulating low flows. For both the calibration and validation periods, the correspondence of the simulated to the observed hydrographs was higher for the annual time step than for the monthly simulation, as reflected by a higher NS for the annual time step.


Santana do Mundaú (Alagoas, PE)
P-factor= 0.60
R-factor= 0.87
R²= 0.72
NS= 0.71
95PPU
Observed
Simulated
A
Calibration
Validation
Discharge (m³ s⁻¹)
40
30
20
10
0
2003
2004
2005
2006
2007
2008
2009
2010
Date
Santana do Mundaú (Alagoas, PE)
P-factor= 0.88
R-factor= 1.18
R²= 0.78
NS= 0.78
PBIAS= -2.4
95PPU
Observed
Simulated
B
Calibration
Validation
Discharge (m³ s⁻¹)
100
80
60
40
20
0
Jan-03
Jun-03
Nov-03
Apr-04
Sep-04
Feb-05
Jul-05
Dec-05
May-06
Oct-06
Mar-07
Aug-07
Jan-08
Jun-08
Nov-08
Apr-09
Sep-09
Feb-10
Jul-10
Dec-10
May-11
Oct-11
Mar-12
Aug-12
Jan-13
Jun-13
Nov-13
São José da Laje (Alagoas, PE)
P-factor= 1.00
R-factor= 1.40
R²= 0.93
NS= 0.92
PBIAS= 1.1
95PPU
Observed
Simulated
C
Calibration
Validation
Discharge (m³ s⁻¹)
20
15
10
5
0
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Date
São José da Laje (Alagoas, PE)
P-factor= 0.80
R-factor= 0.92
R²= 0.56
NS= 0.55
PBIAS= 2.2
95PPU
Observed
Simulated
D
Calibration
Validation
Discharge (m³ s⁻¹)
60
40
20
0
Jan-03
Jun-03
Nov-03
Apr-04
Sep-04
Feb-05
Jul-05
Dec-05
May-06
Oct-06
Mar-07
Aug-07
Jan-08
Jun-08
Nov-08
Apr-09
Sep-09
Feb-10
Jul-10
Dec-10
May-11
Oct-11
Mar-12
Aug-12
Jan-13
Jun-13
União dos Palmares (Alagoas, PE)
P-factor= 0.80
R-factor= 0.95
R²= 0.86
NS= 0.75
PBIAS= -8.2
95PPU
Observed
Simulated
E
Calibration
Validation
Discharge (m³ s⁻¹)
100
75
50
25
0
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Date
União dos Palmares (Alagoas, PE)
P-factor= 0.93
R-factor= 1.81
R²= 0.64
NS= 0.62
PBIAS= 6.6
95PPU
Observed
Simulated
F
Calibration
Validation
Discharge (m³ s⁻¹)
400
300
200
100
0
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
Date

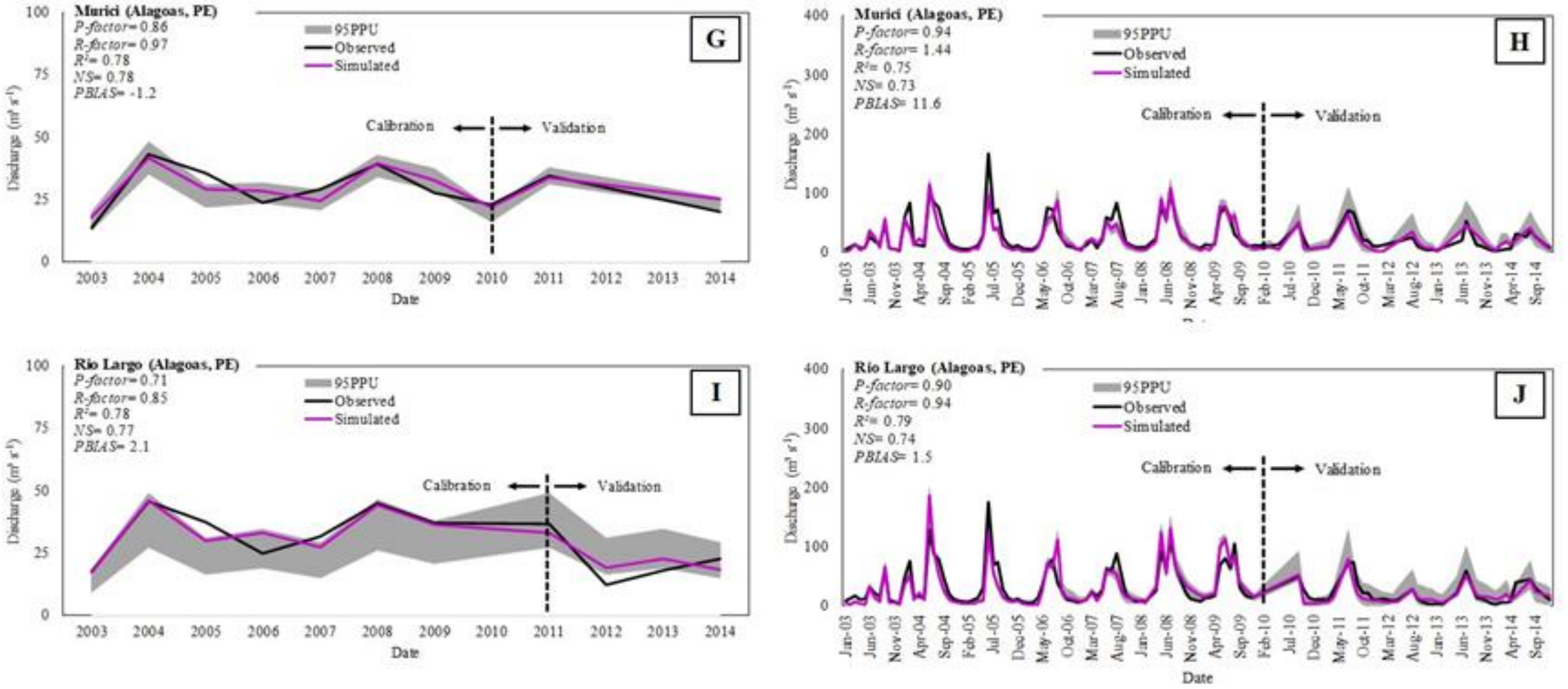


Fig. 3. Full-scale SWAT-CUP illustration showing the observed, the best simulation and 95% uncertainty prediction (95PPU) for the five stations of the Mundaú River Basin in annual and monthly time steps, respectively. P-factor is the percentage of observed data involved by the modeling result, at 95PPU, while the R-factor is the thickness of the 95PPU. At each station, about two-thirds of the data were used for calibration and the remainder for validation.

The rainfall rates over the studied years are presented in Figure 4. It is possible to verify that 2004 was an unusually wet year (1,493.3 mm total annual rainfall), with eight months of the year receiving monthly precipitation over 100 mm. Additionally, 2012 was an extremely dry year, with below-average rainfall (623.5 mm). The mean value for the 2003-2016 period was 1092.5 mm.

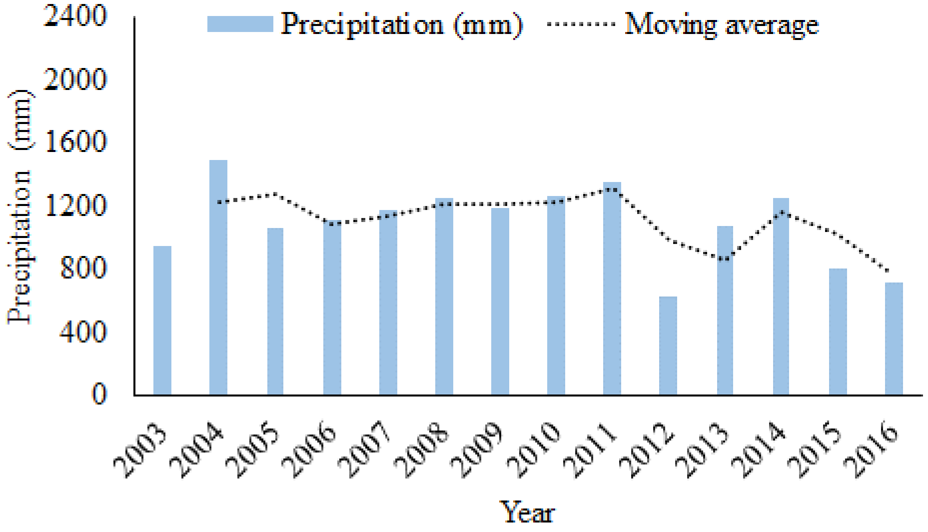


Fig. 4. Total rainfall over the studied years in the Mundaú River Basin

The comparison between two hydrological years with distinct characteristics: 2004 (wet year) and 2012 (dry year) for the five streamflow gauge stations in the Mundaú River Basin is given in Figure 5. The greater rainfall in 2004 was reflected in greater than normal peak flows, increasing from upstream (Santana do Mundaú Station, with observed flow of 9.23 m³ s-1) to downstream (Rio Largo with observed flow of 45.68 m³ s-1) (Fig. 3A, 3C, 3E, 3G, 3I). During the validation period, the hydrographs (Figures 3C, 3E, 3G and 3I) show that 2012 was an extremely dry year, with below-average rainfall and, consequently, small runoff production and lower peaks. This occasioned in lower values of NS because this coefficient result is quite sensitive to estimates of peak flows. In fact, it is easier to calibrate the SWAT model in wet periods, when there are more frequent peak flows, than in dry periods, when flow generation is reduced.

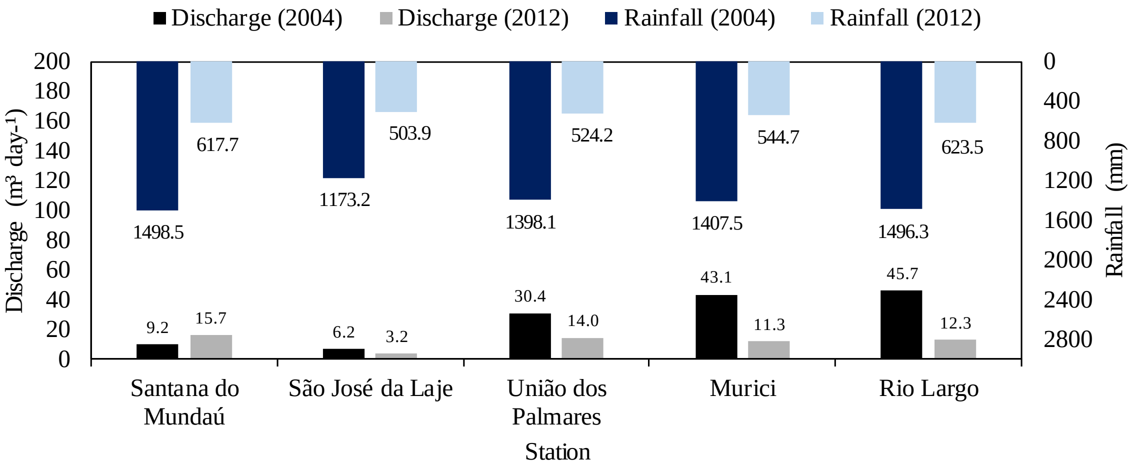


Fig. 5. Comparison between two hydrological years with distinct characteristics: 2004 (wet year) and 2012 (dry year) for the Mundaú River Basin

Table 4 shows the comparison among the statistical indicators (P-factor, R-factor, R², NS and PBIAS) for discharge calibration using the SWAT-CUP semiautomatic calibration method. The calibration step of a hydrological model is subjective and no automatic algorithm is able in replacing the researcher's knowledge in relation to his study area. Therefore, the calibration procedures and uncertainty analysis are closely connected, and no calibration should be performed without quantifying the degree of uncertainty associated to the model prediction (Abbaspour et al., 2015). In hydrological modeling, it is very important to carry out a careful model calibration, that is, to parameterize it adequately, in order to reduce much of the uncertainties associated to modeling. Over estimation might lead to an excessive application of mitigating measures, while under estimation can lead to insufficient preparation for extreme conditions (Duan et al., 1992; Van Griensven et al., 2008; Kumar et al, 2017).

Table 4. Summary statistics of calibration, validation and uncertainty analysis of the SWAT model by the Split-sample Test method, in annual and monthly time steps in the five streamflow gauge stations of the Mundaú River Basin

Statistics	Santana do Mundaú (756 km²)		São José da Laje (1143 km²)		União dos Palmares (998 km²)		Murici (385 km²)		Rio Largo (808 km²)	
	Calibration									
	Annual	Monthly	Annual	Monthly	Annual	Monthly	Annual	Monthly	Annual	Monthly
p-factor	0.60	0.88	1.00	0.80	0.80	0.93	0.86	0.94	0.71	0.90
r-factor	0.87	1.18	1.40	0.92	0.95	1.81	0.97	1.44	0.85	0.94
R^2	0.72	0.78	0.93	0.56	0.86	0.64	0.78	0.75	0.78	0.79
NS	0.71	0.78	0.92	0.55	0.75	0.62	0.78	0.73	0.77	0.74
PBIAS	2.90	-2.40	1.10	2.20	-8.20	6.60	-1.20	11.60	2.10	1.50
	Validation									
p-factor	1.00	0.67	0.67	0.85	1.00	0.50	1.00	0.72	0.75	0.90
r-factor	6.55	1.18	0.72	0.77	2.21	1.03	0.90	1.39	0.72	1.62
R^2	0.99	0.66	0.68	0.72	0.63	0.76	0.79	0.69	0.75	0.74
NS	0.53	0.64	0.68	0.72	0.61	0.62	0.76	0.69	0.69	0.72
PBIAS	-9.20	13	-2.00	-7.10	-6.20	24.20	-4.30	1.20	-3.60	11.00

The calibration results show high values of p-factor (0.79 – annual and 0.89 – monthly, in average) which indicates the high percentage (79% and 89%) in matching measured data in the 95PPU plot (Fig. 3), and the range of uncertainty in the output values. The thickness of uncertainty band can be seen in 95PPU by the r-factor (1.01 – annual and 1.26 – monthly, in average). A large p-factor and a r-factor close to 1 indicate that the uncertainty in simulation were properly predicted by the model. In the validation period, the values of p-factor (0.88 – annual and 0.73 – monthly, in average) were also above 70% and r-factor values were close to 1 (2.22 – annual and 1.20 – monthly, in average), indicating good adjustment between the simulation results and the observed discharge data. The model uncertainty may be associated with several factors, such as natural and anthropogenic processes that occur in the watershed but which are not included in the model (Yang et al., 2008), the uncertainty in soil and water parameters as well as the climate variation during the modeling period (Abbaspour et al., 2015).

The values of the determination coefficient (R^2) varied between 0.72 and 0.93 in the calibration phase in the annual time step; and between 0.56 and 0.79 in the monthly time step. For the validation phase, R^2 values ranged from 0.63 to 0.99 in the annual time step, and from 0.66 to 0.76 in the monthly time step. These results indicate that, in general, the performance of the SWAT model might be considered satisfactory for the MRB, since there were values of R^2 above 0.80. A multi-variable calibration of the SWAT model with remote sensing evapotranspiration data and observed flow data in the Upper Rio Negro Basin (3,453 km^2), in the Santa Catarina and Paraná States, Brazil, were performed by Franco and Bonumá (2017). The authors found R^2 values of 0.76 and 0.78 in the calibration phase and of 0.58 and 0.75 in the validation phase, using observed flow data, and considering different temporal strategies for calibration/ validation. Silva and Medeiros (2014), when performing a hydro-sedimentological analysis using the SWAT model for the Experimental Basin of São João do Cariri (13.5 km^2), found an R^2 value equal to 0.88 during manual calibration with discharge data.

The values of the Nash-Sutcliffe model efficiency (NS), which depict the model precision, especially in the representation of peak flows, varied among stations from 0.71 to 0.92, in the calibration phase, in the annual time step; and from 0.55 to 0.78 in the monthly time step, considered as "satisfactory" and "very good" performances, according to the classification proposed by Moriasi et al. (2007). In the validation phase, NS values ranged from 0.53 to 0.76 in the annual time step and from 0.62 to 0.72 in the monthly time step, also considered "satisfactory" and "very good" performances (Table 4). By observing these results, it is possible to verify that, in general, the performance of the SWAT model was better for the annual time step, when compared to the monthly time step, both for the calibration and validation phases. This probably occurred as the monthly errors are smoothed when considering annual data. In addition, the NS value for the calibration phase was significantly higher than the value obtained for validation. In fact, NS values were expected to be higher for calibration – the phase at which the parameters are modified in order to allow the model to achieve good performances - than in the validation – the phase during which the parameters are no longer modified. Most worldwide studies involving the SWAT model achieved good performances during the calibration phase. However, performance during validation is often much worse than for calibration. This is often due to the "over-calibration" occurred in the process, leading to unsatisfactory results for the validation phase.

There are several studies in the literature that used the NS to test the SWAT efficiency for simulating the discharge behavior in watersheds around the world. Andrade et al. (2013) found NS values of 0.66 and 0.87 for the calibration and validation phases in the Jaguara River Basin (32 km²), Brazil. In turn, Xue et al. (2014) found NS values of 0.81 and 0.83 for calibration and validation in the Huolin River Basin (8,102 km²), China. Brighenti et al. (2016) found from unsatisfactory to satisfactory NS results in the Negrinho River Basin (200 km²), Brazil. Blainski et al. (2017) found NS values of 0.66 and 0.89 for the calibration and validation in the Camboriú River Basin (195 km²), Brazil. In comparison with previous work involving calibration and validation of the SWAT model, in several parts of the world, the NS values obtained for the MRB were satisfactory, thus indicating that the SWAT model was able to represent the main hydrological processes in the MRB, and yet suggesting that the model could be useful for simulation of similar watersheds.

The values of PBIAS varied (in absolute terms) between 1.1 and 8.2 in calibration for the annual time step; and between 1.5 and 11.6 for the monthly time step. For the validation phase, PBIAS values ranged from 2.0 to 9.2 for the annual time step, and from 1.2 to 24.2 for the monthly time step. These results indicate that the SWAT model presented "satisfactory" and "very good" results, according to the classification proposed by Moriasi et al. (2007). In comparison, Pereira et al. (2014) found PBIAS values of 7.2 and 14.1 in the calibration and validation phases in the Galo Creek Watershed, Brazil.

4.3.3 Calibration and uncertainty analysis for soil moisture

In addition to the discharge data, daily soil moisture data were used in this study. Figure 6 shows the temporal comparison between observed and simulated soil moisture for the calibration and validation phases, for a sub-basin in the Mundaú Basin. In both steps, a satisfactory correspondence was found between measured and simulated data. This performance could be verified by the obtained statistical indices, with NS values of 0.53 and 0.52, and PBIAS of 0.4% and -1.1%, in the calibration and validation steps, respectively. These results represent "satisfactory" and "very good" performances, according to the classification proposed by Moriasi et al. (2007). For this basin, the values of PBIAS for soil moisture were better than for discharge (Table 4). However, the NS values have not improved when compared to the results of discharge calibration. According to Vervoort et al. (2014), the calibration process helps to improve the estimation of peak flows and recess periods by the model. However, when using soil moisture data, there is not necessarily a better event-based response during the simulation. This may be a justification for the Nash values have not increased when using soil moisture data, compared to the calibration adopting the discharge data only.

According to the result of calibration with soil moisture data, 100% of the observed data lies within the uncertainty band (p-factor = 1), but this uncertainty may be high, since the value of the r-factor was not close to 1 (r-factor = 7.08) (Fig. 6). This could be related to the uncertainty in the soil characteristics, but may also be related to the calibration scheme.

According to Uniyal et al. (2017), the model uncertainty could be associated to the simplified soil water equations of SWAT and to the considerable heterogeneity in the observed soil moisture data. These uncertainties could be better evaluated through real-time updating, by collecting soil moisture data (Wanders et al., 2014; Alvarez-Garreton et al., 2015; Lievens et al., 2015).

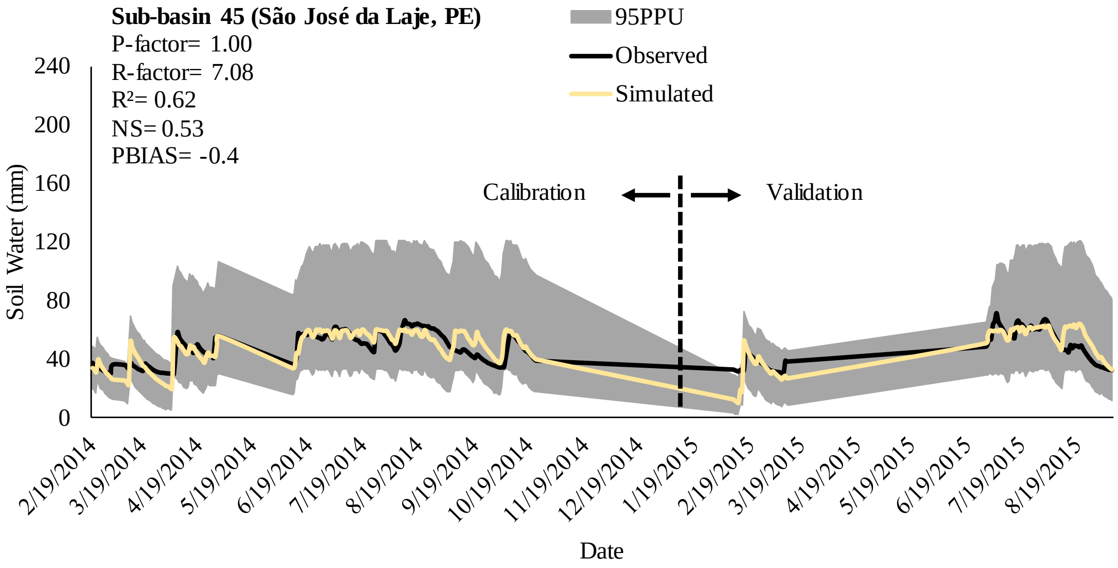


Fig. 6. Comparison between soil water content observed and simulated by the SWAT model, in the calibration and validation phases

Figure 7 shows the simulation error (Error, △ = Simulated – Observed) between observed and simulated soil water content (mm) for the calibration and validation phases. The error plot clearly indicates minimal or even zero errors in simulations for a significant portion of the time, suggesting, according to the simulation error, that the soil water calibration improved model performance. Kundu et al. (2017) found that RMSE error values were reduced in the calibrated model when adopting soil moisture data. According to Li et al. (2018), introducing soil moisture into the model calibration really strengthens the model ability in the forecasting of hydrologic processes, since the physical connection between soil moisture and discharge is very strong in process-based models.

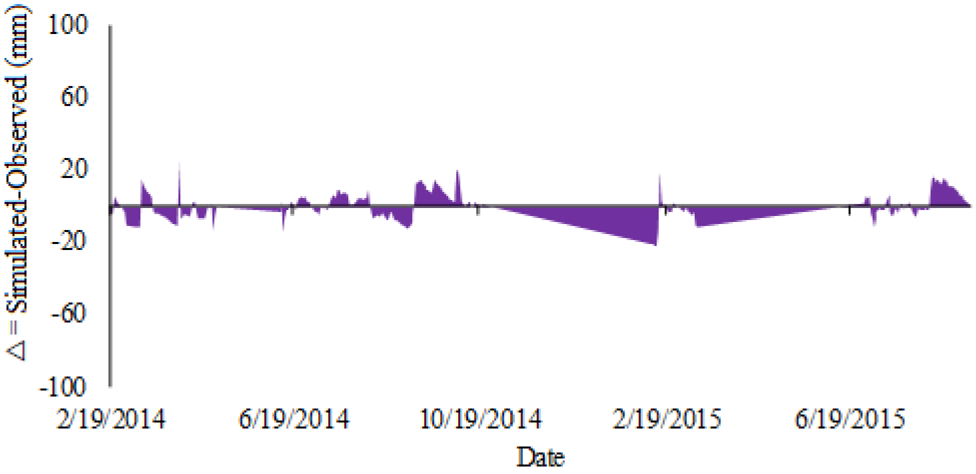


Fig. 7. Simulation error (Error, △ = Simulated – Observed) between soil water content (mm) observed and simulated by the SWAT model, in the calibration and validation phases

It is important to mention that there are still very few studies in the literature that has used soil moisture data as an alternative to calibrate the SWAT model, and most research has applied soil moisture data from remote sensing (Rajib et al., 2016; Kundu et al., 2017; Uniyal et al., 2017). Rajib et al. (2016) performed a multi-objective calibration of the SWAT model using spatially distributed remotely sensed soil moisture and discharge. According to the authors, satisfactory streamflow simulations could be obtained without using any soil moisture information in the calibration process. However, a significant improvement in PBIAS was observed in soil moisture outputs, indicating the model ability to reduce uncertainty/equifinality problems. Kundu et al. (2017) used data remotely sensed surface soil moisture to calibrate the SWAT model at the Warrego river catchment (69,290 km2) and verified that soil moisture was a useful variable in reducing model calibration uncertainties. According to the authors, the use of soil moisture data enhanced model discharge predictions. Uniyal et al. (2017) evaluated the spatial and temporal patterns of soil moisture simulated by the SWAT at 30 cm depth with indirect soil moisture estimates from Landsat images and found that the uncertainty band for soil moisture was narrower.

These results indicate that the SWAT model can be calibrated with alternative data, such as soil moisture, evapotranspiration, leaf area index (LAI), water table levels, among others, to enhance model performance. However, it is necessary to evaluate the associated uncertainties, mainly because of the scale (spatial resolution) between discharge and the alternative data. It is worth mentioning that these data must have high reliability and consistency to allow an adequate calibration. The great importance of using alternative data in the calibration process is in the fact that a series of discharge data is not always available, as is the case in some Brazilian semiarid watersheds with intermittent flow regimes.

4.3.4 Flow durations curves analyses

According to Gomes and Fernandes (2017), it is essential to understand the hydrological behavior of watersheds to get more precise results for planning all demands for water use, through reference flow procedures. One of the alternatives to determine water availability in a watershed is the construction of flow duration curves. Discharges with probability of exceedance equal to or over 90% are essential in hydrological studies for planning water supply, since they indicate the quantity of water that can be guaranteed with the corresponding certainty level. Discharges with probability of exceedance of 50% are important to evaluate the maximum possible flow to be regularized. The probability of exceedance equal to or lower than 10% are applied in studies associated to extreme flood events (Oliveira et al., 2015).

Figure 8 illustrates the observed and simulated flow duration curves by the SWAT model, in the calibration (left) and validation (right) steps.

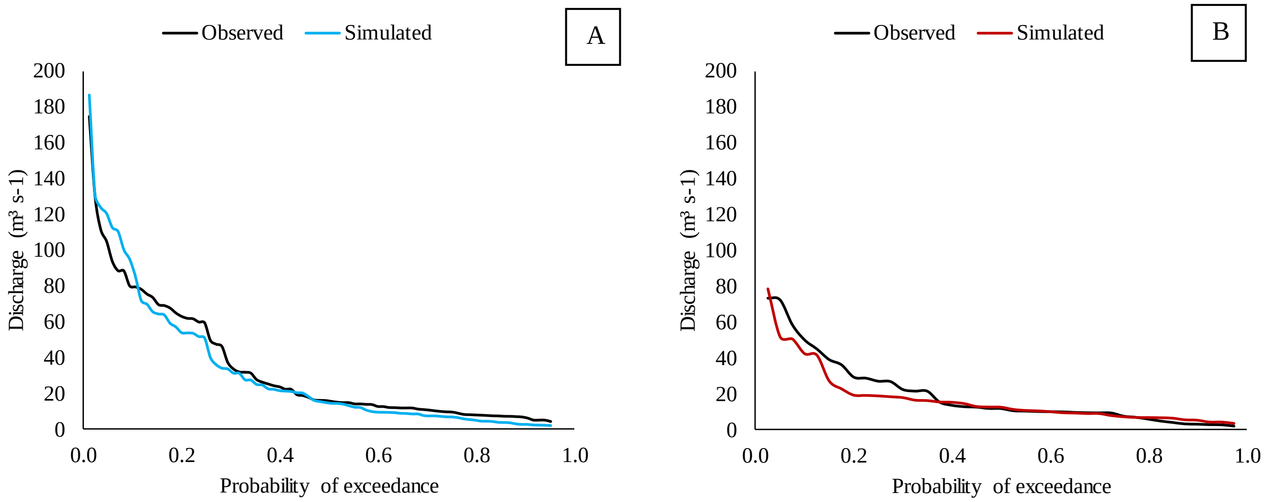


Fig. 8. Observed and simulated flow duration curves in the calibration (A) and validation (B) steps of the SWAT model for the Mundaú River Basin (MRB)

By observing the flow duration curves, both in the calibration and in the validation periods, it can be observed that, in general, simulated flows below the 40% frequency were underestimated. In relation to the flow rates above 80%, the lowest flow rates, the observed data were underestimated in calibration and overestimated in the validation phase, with mean errors of 20.42% and 23.71%, respectively. In the calibration period, the observed mean streamflow was equal to 33.74 m³ s-1 and the simulated value was equal to 32.02 m³ s-1, for monthly time step. In the validation period, the observed average streamflow was of 19.47 m³ s-1 and the simulated was of 17.32 m³ s-1. Based on these differences, which were of small magnitude, it can be verified that the SWAT model adequately simulated the flow duration curves for the MRB, demonstrating its quality and potential as a numerical tool for water resources management.

4.4 Conclusions

In this study, uncertainties were evaluated in using both discharge and soil moisture experimental data on SWAT calibration and validation for the Mundaú River Basin. Considering the representativeness of the watershed and the data scarcity for hydrological modeling, the results are very satisfactory. A good agreement between simulated and measured annual and monthly streamflow was demonstrated by the determination coefficient (R^2), the Nash-Sutcliffe model efficiency (NS) and the percent bias (PBIAS), with "satisfactory" and "very good" performances.

Although there is a considerable amount of uncertainty, the use of a series of alternative data to calibrate and validate the SWAT model (e.g soil moisture data) is a feasible and promising option for hydrological modeling, especially when hydrological and meteorological data series has low availability, as is the case in some of the Brazilian semiarid watersheds. The use of soil moisture improved the calibration results, with better value for the PBIAS. Moreover, the adequate representation of soil moisture in the calibration process, in addition to reducing the uncertainties in hydrological modeling, is extremely valuable because the Brazilian semiarid is a region with limited water flow volume in the rivers, resulting in a dense network of intermittent watercourses, with zero flows during the dry period. Thus, the knowledge of the behavior of this variable becomes relevant, as the soil moisture is one of the main variables affecting crops development, flow generation and agricultural production systems in scarcity periods.

Finally, the outcomes achieved were very encouraging. SWAT allows the hydrological processes on the Mundaú to be suitably represented. The calibrated SWAT model for the Mundaú River Basin might be used for scenarios generation. The fitted parameters can be adopted to other study periods or to similar watersheds. The results can also be useful for areas with few data and information availability, at scales from micro watershed to large watersheds.

References

Abbaspour, K.C., Johnson, C.A., Van Genuchten, M.T., 2004. Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure. Vadose Zone Journal, 3, 1340-1352. http://dx.doi.org/10.2136/vzj2004.1340.

Abbaspour, K.C., 2015. SWAT-CUP: SWAT Calibration and Uncertainty Programs - A User Manual. Eawag: Swiss Federal Institute of Aquatic Science and Technology. 100p.

Abbaspour, K.C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H., Klove, B., 2015. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. Journal of Hydrology, 524, 733–752. http://dx.doi.org/10.1016/j.jhydrol.2015.03.027.

Abbaspour, K.C., Vaghefi, S.A., Srinivasan, R., 2018. A guideline for successful calibration and uncertainty analysis for soil and water assessment: A review of papers from the 2016 International SWAT Conference. Water, 10, 6, 1-18. https://doi.org/10.3390/w10010006.

Abbott, M.B., Refsgaard, J.C., 1996. Distributed hydrological modelling. Dordrecht: Springer Netherlands, 22.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M., Sparovek, G., 2014. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift, 22, 6, 711–728. https://doi.org/10.1127/0941-2948/2013/0507.

Alvarez-Garreton, C., Ryu, D., Western, A.W., Su, C.H., Crow, W.T., Robertson, D.E., Leahy, C., 2015. Improving operational flood ensemble prediction by the assimilation of satellite soil moisture: comparison between lumped and semi-distributed schemes. Hydrol. Earth Syst. Sc., 19, 4, 1659–1676. https://doi.org/10.5194/hess-19-1659-2015.

Andrade, C.W.L., Montenegro, S.M.G.L., Lima, J.R.S., Montenegro, A.A.A., Srinivasan, R., 2017a. Análise de sensibilidade de parâmetros do modelo SWAT em uma sub-bacia da Região Nordeste, Brasil. Revista Brasileira de Geografia Física, 10, 440-453. http://dx.doi.org/10.5935/1984-2295.20170027.

Andrade, C.W.L., Montenegro, S.M.G.L., Lima, J.R.S., Montenegro, A.A.A., Magalhães, A.G., 2017b. Modelagem hidrológica sob mudanças na cobertura vegetal de uma bacia hidrográfica no Nordeste do Brasil. Journal of Environmental Analysis and Progress, 2, 3, 239-248. http://dx.doi.org/10.24221/jeap.2.3.2017.1446.239-248.

Andrade, M.A., Mello, C.R., Beskow, S., 2013. Simulação hidrológica em uma bacia hidrográfica representativa dos Latossolos na região Alto Rio Grande, MG. Revista Brasileira de Engenharia Agrícola e Ambiental, 17, 69-76. http://dx.doi.org/10.1590/S1415-43662013000100010.

Arnold, J.G., Kiniry, J.R., Srinivasan, R., Williams, J.R., Haney, E.B., Neitsch, S.L., 2012a. Input/Output Documentation version 2012. Texas Water Resources Institute – TR-439. 650p.

Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., Van Griensven, A., Van Liew, M.W., Kannan, N., Jha, M.K., 2012b. SWAT: Model use calibration and validation. Transactions of the ASABE, 55, 1494-1508. http://dx.doi.org/10.13031/2013.42256.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment part I: model development. Journal of the American Water Resources Association, 34, 73-89. http://dx.doi.org/10.1111/j.1752-1688.1998.

Beven, K., 2006. A manifesto for the equifinality thesis. Journal of Hydrology, 320, 18-36. http://dx.doi.org/10.1016/j.jhydrol.2005.07.007.

Beven, K., 2012. Rainfall-runoff modelling: the primer, third ed. Chichester: Lancaster University.

Blainski, E., Acosta, E., Nogueira, P.C.P., 2017. Calibração e validação do modelo SWAT para simulação hidrológica em uma bacia hidrográfica do litoral norte catarinense. Revista Ambiente e Água, 12, 226-237. http://dx.doi.org/10.4136/ambi-agua.1951.

Bressiani, D.A., 2016. Coping with hydrological risks through flooding risk index, complex watershed modeling, different calibration techniques, and ensemble streamflow forecasting. Thesis (Doctorade). São Carlos Engineering School – University of São Paulo. 192p.

Bressiani, D.A., Gassman, P.W., Fernandes, J.G., Garbossa, L.H.P., Srinivasan, R., Bonumá, N.B., Mendiondo, E.M., 2015. Review of Soil and Water Assessment Tool (SWAT) applications in Brazil: Challenges and prospects. International Journal of Agricultural and Biological Engineering, 8, 9-35. http://dx.doi.org/10.3965/j.ijabe.20150803.1765.

Brighenti, T.M., Bonumá, N.B., Chaffe, P.L.B., 2016. Calibração hierárquica do modelo SWAT em uma bacia hidrográfica Catarinense. Revista Brasileira de Recursos Hídricos, 21, 53-64. http://dx.doi.org/10.21168/rbrh.v21n1.p53-64.

Brouziyne, Y., Abouabdillah, A., Bouabid, R., Benaabidate, L., Oueslati, O., 2017. SWAT manual calibration and parameters sensitivity analysis in a semiarid watershed in North-western Morocco. Arabian Journal of Geosciences, 10, 427-440. http://dx.doi.org/10.1007/s12517-017-3220-9.

Chow, V.T., 1959. Open-channel hydraulics: New York, McGraw-Hill, 680p.

Daggupati, P., Yen, H., White, M.J., Srinivasan, R., Arnold, J.G., Keitzer, C.S., Sowa, S.P., 2015. Impact of model development, calibration and validation decisions on hydrological simulations in West Lake Erie Basin. Hydrological Processes, 29, 5307-5320. http://dx.doi.org/10.1002/hyp.10536.

Duan Q., Sorooshian S., Gupta V.K., 1992. Effective and efficient global optimization for conceptual rainfall-runoff models. Water Resources Research, 28, 4, 1015–1031. https://doi.org/10.1029/91WR02985.

Engel B., Storm D., White M., Arnold J.G., Arabi M., 2007. A hydrologic/ water quality model application protocol. JAWRA, 43, 5, 1223–1236. https://doi.org/10.1111/j.1752-1688.2007.00105.x.

Fontes Júnior, R.V.P., 2016. Experimentação e modelagem hidrológica aplicada à bacia do alto Ipanema-PE. Thesis (Doctorade). Federal Rural University of Pernambuco. 156p.

Franco, A.C.L., Bonumá, N.B., 2017. Multi-variable SWAT model calibration with remotely sensed evapotranspiration and observed flow. Brazilian Journal of Water Resources, 22, 1-11. http://dx.doi.org/10.1590/2318-0331.011716090.

Fukunaga, D.C., Cecílio, R.A., Zanetti, S.S., Oliveira, L.T., Caiado, M.A.C., 2015. Application of the SWAT hydrologic model to a tropical watershed at Brazil. Catena, 125, 206-213. http://dx.doi.org/10.1016/j.catena.2014.10.032.

Gomes, R.R.K.A., Fernandes, L.L. 2017. Hydrological characterization of the Araguaia River through reference flows. Applied Water Science, 7, 1-10. http://dx.doi.org/10.1007/s13201-017-0622-5.

Gupta, H.V., Sorooshian, S., Yapo, P.O., 1999. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. J. Hydrologic Eng., 4, 2, 135-143. https://doi.org/10.1061/(ASCE)1084-0699(1999)4:2(135).

Hammouri, N., Adamowski, J., Freiwan, M., Prasher, S., 2017. Climate change impacts on surface water resources in arid and semiarid regions: a case study in northern Jordan. Acta Geodaetica et Geophysica, 52, 141-156. http://dx.doi.org/10.1007/s40328-016-0163-7.

Harmel, R.D., Smith, P.K., 2007. Consideration of measurement uncertainty in the evaluation of goodness-of-fit in hydrologic and water quality modeling. Journal of Hydrology, 337, 326– 336. https://doi:10.1016/j.jhydrol.2007.01.043.

Kenard, M.J., Mackay, S.J., Pusey, B.J., Olden, J.D., Marsh, N., 2010. Quantifying uncertainty in estimation of hydrologic metrics for ecohydrological studies. River Research and Applications, 26, 2, 137-156. https://doi.org/10.1002/rra.1249.

Klemes, V., 1986. Operational testing of hydrological simulation models. Hydrological Sciences Journal, 31, 13-24. http://dx.doi.org/10.1080/02626668609491024.

Kumar, N., Singh, S.K., Srivastava, P.K., Narsimlu, B., 2017. SWAT Model calibration and uncertainty analysis for streamflow prediction of the Tons River Basin, India, using Sequential Uncertainty Fitting (SUFI-2) algorithm. Model. Earth Syst. Environ., 3, 30, 1-13. https://doi.org/10.1007/s40808-017-0306-z.

Kundu, D., Vervoort, R.W., van Ogtrop, F.F., 2017. The value of remotely sensed surface soil moisture for model calibration using SWAT. Hydrological Processes, 31, 2764–2780. https://doi.org/10.1002/hyp.11219.

Leal, I.R., Silva, J.M.C., Tabarelli, M., Lacher Junior, T.E., 2005. Changing the course of biodiversity conservation in the Caatinga of Northeastern Brazil. Conservation Biology, 19, 701-706. http://dx.doi.org/10.1111/j.1523-1739.2005.00703.x.

Li, Y., Grimaldi, S., Pauwels, V.R.N., Walker, J.P., 2018. Hydrologic model calibration using remotely sensed soil moisture and discharge measurements: The impact on predictions at gauged and ungauged locations. Journal of Hydrology, 557, 897–909. https://doi.org/10.1016/j.jhydrol.2018.01.013.

Lievens, H., Tomer, S.K., Al Bitar, A., De Lannoy, G.J.M., Drusch, M., Dumedah, G., Hendricks Franssen, H.J., Kerr, Y.H., Martens, B., Pan, M., Roundy, J.K., Vereecken, H., Walker, J.P., Wood, E.F., Verhoest, N.E.C., Pauwels, V.R.N., 2015. SMOS soil moisture assimilation for improved hydrologic simulation in the Murray Darling Basin, Australia. Remote Sens. Environ., 168, 146–162. https://doi.org/10.1016/j.rse.2015.06.025.

Lin, K., Lv, F., Chen, L., Singh, V.P., Zhang, Q., Chen, X., 2014. Xinanjiang model combined with Curve Number to simulate the effect of land use change on environmental flow. Journal of Hydrology, 519, 3142–3152. https://doi.org/10.1016/j.jhydrol.2014.10.049.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Binger, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE, 50, 3, 885-900. http://dx.doi.org/10.13031/2013.23153.

Narsimlu, B., Gosain, A.K., Chahar, B.R., Singh, S.K., Srivastava, P.K., 2015. SWAT model calibration and uncertainty analysis for streamflow prediction in the Kunwari River Basin, India, using sequential uncertainty fitting. Environmental Processes, 2, 1, 79–95. https://doi.org/10.1007/s40710-015-0064-8.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models: Part 1. A

discussion of principles. Journal of Hydrology, 10, 282-290. http://dx.doi.org/10.1016/0022-1694(70)90255-6.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2005. Soil and water assessment tool: Theoretical documentation version 2005. Temple: Blackland Research Center, 541p.

Oliveira, G.G., Pedrollo, O.C., Castro, N.M.R. 2015. Stochastic approach to analyzing the uncertainties and possible changes in the availability of water in the future based on scenarios of climate change. Hydrology and Earth System Sciences, 19, 3585–3604. http://dx.doi.org/10.5194/hess-19-3585-2015

Oliveira Júnior, J.A.S., Souza, E.S., Correa, M.M., Lima, J.R.S., Souza, R.M.S., Silva Filho, L.A., 2014. Variabilidade espacial de propriedades hidrodinâmicas de um Neossolo Regolítico sob pastagem e caatinga. Revista Brasileira de Engenharia Agrícola e Ambiental, 18, 631–639. http://dx.doi.org/10.1590/S1415-43662014000600010

ONU – United Nations Organization. Rio+20: United Nations Conference on Sustainable Development. Rio de Janeiro, Brazil 20-22 June, 2012 A/CONF.216/L.1. Available in: <http://www.uncsd2012.org/thefuturewewant.html>. Accessed in: July, 2015.

Pereira, D.R., Martinez, M.A., Almeida, A.Q., Pruski, F.F., Silva, D.D., Zonta, J.H., 2014. Hydrological simulation using SWAT model in headwater Basin in Southeast Brazil. Engenharia Agrícola, 34, 789-799. http://dx.doi.org/10.1590/S0100-69162014000400018.

Rajib, M.A., Merwade, V., Yu, Z., 2016. Multi-objective calibration of a hydrologic model using spatially distributed remotely sensed/in-situ soil moisture. Journal of Hydrology, 536, 192–207. http://dx.doi.org/10.1016/j.jhydrol.2016.02.037.

Rallison, R.E., Miller, N., 1981. Past, present and future SCS runoff procedure, in: Singh, V.P. (Ed.). Rainfall runoff relationship. Littleton, USA: Water Resources Publication, pp. 353-364.

Santos Neto, S.M., 2015. Avaliação da dinâmica da água na resposta de sensor tipo TDR em solos de Pernambuco. Dissertation (Master). Federal University of Pernambuco. 97p.

Schaefli, B., Hingray, B., Musy, A., 2004. Improved calibration of hydrological models: use of a multi-objective evolutionary algorithm for parameter and model structure uncertainty estimation. In: Hydrology: Science and Practice for the 21st Century, Webb, B. (ed.). British Hydrological Society: London, 362-371.

Silva, R.M., Medeiros, I.C., 2014. Análise hidrossedimentológica em ambiente SIG usando o modelo SWAT. GeoFocus, 14, 211-231. Available in: http://www.geofocus.org/index.php/geofocus/article/view/308.

Strauch, M., Bernhofer, C., Koide, S., Volk, M., Lorz, C., Makeschin, F., 2012. Using precipitation data ensemble for uncertainty analysis in SWAT streamflow simulation. Journal of Hydrology, 414–415, 413–424. https://doi.org/10.1016/j.jhydrol.2011.11.014.

Tuo, Y., Duan, Z., Disse, M., Chiogna, G., 2016. Evaluation of precipitation input for SWAT modeling in Alpine catchment: A case study in the Adige river basin (Italy). Science of The Total Environment, 573, 66-82. https://doi.org/10.1016/j.scitotenv.2016.08.034.

Uniyal, B., Dietrich, J., Vasilakos, C., Tzoraki, O., 2017. Evaluation of SWAT simulated soil moisture at catchment scale byfield measurements and Landsat derived indices. Agricultural Water Management, 193, 55–70. http://dx.doi.org/10.1016/j.agwat.2017.08.002.

Vaghefi, S.A., Mousavi, S.J., Abbaspour, K.C., Srinivasan, R., Yang, H., 2014. Analyses of the impact of climate change on water resources components, drought and wheat yield in semiarid regions: Karkheh River Basin in Iran. Hydrological Processes, 28, 2018–2032. https://dx.doi.org/10.1002/hyp.9747.

Van Griensven A., Meixner T., Srinivasan R., Grunwals S., 2008. Fit-for-purpose analysis of uncertainty using split-sampling evaluations. Hydrological Sciences Journal, 53, 5, 1090–1103. https://doi.org/10.1623/hysj.53.5.1090.

Vervoort, R.W., Miechels, S.F., van Ogtrop, F.F., Guillaume, J.H.A., 2014. Remotely sensed evapotranspiration to calibrate a lumped conceptual model: Pitfalls and opportunities. Journal of Hydrology, 519, 3223–3236. https://doi.org/10.1016/j.jhydrol.2014.10.034.

Wallace, C.W., Flanagan, D.C., Engel, B.A., 2018. Evaluating the effects of watershed size on

SWAT calibration. Water, 10, 898, 1-27. https://doi.org/10.3390/w10070898.

Wanders, N., Karssenberg, D., de Roo, A., de Jong, S.M., Bierkens, M.F.P., 2014. The suitability of remotely sensed soil moisture for improving operational flood forecasting. Hydrol. Earth Syst. Sc., 18, 6, 2343–2357. https://doi.org/10.5194/hess-18-2343-2014.

Werneck, F.P., 2011. The diversification of eastern South American open vegetation biomes: Historical biogeography and perspectives. Quaternary Science Reviews, 30, 1630-1648. https://dx.doi.org/10.1016/j.quascirev.2011.03.009.

Xue, C., M.Asce, B.C., Wu, H., 2014. Parameter uncertainty analysis of surface flow and sediment yield in the Huolin Basin, China. Journal of Hydrologic Engineering, 19, 1224-1236. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000909.

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

Zettam, A., Taleb, A., Sauvage, S., Boithias, L., Belaidi, N., Sánchez-Pérez, J.M., 2017. Water, 9, 216-234. https://doi.org/10.3390/w9030216.

Zhang, D., Chen, X., Yao, H., Lin, B., 2015. Improved calibration scheme of SWAT by separating wet and dry seasons. Ecological Modelling, 301, 54-61. https://doi.org/10.1016/j.ecolmodel.2015.01.018.

Zhang, X., Liang, F., Srinivasan, R., Van Liew, M., 2009. Estimating uncertainty of streamflow simulation using Bayesian neural networks. Water Resources Research, 45, 1-16. https://doi:10.1029/2008WR007030.

5. *Modeling runoff response to land use changes using SWAT model in the Mundaú watershed, Brazil*

A version of this chapter will be shortly submitted to a peer-review journal.

Abstract

Land use change has great influence on runoff process of any watershed and the deepening of this theme is important to assist decision making, within the scope of water resources management. The present study was conducted for Mundaú River Basin (MRB) using Soil and Water Assessment Tool (SWAT) model. The aim of the study is assessing the issue of land use change and its effect on evapotranspiration, surface runoff and sediment yield. Input data like land use, topography, weather and soil data features are required to undertake watershed simulation. Two scenarios of land use were analyzed over a period of 30 years, which were: a regeneration scenario (referring to use in the year 1987) and another scenario of degradation (referring to use in the year 2017). Land use maps for 1987 and 2017 were acquired from satellite images. Overall, during the last three decades, 76.4% of forest were lost in the MRB. On the other hand, grazing land increased in 2017 at little more than double the area that existed in 1987. Changes in land use over the years resulted in an increase of about 37% in water yield of the MRB. Changes have led to increased processes such as surface runoff and sediment yield, and in the decrease of evapotranspiration. The spatial and temporal distribution of land use controls the water balance and sediment production in the MRB.

Keywords: Land use, Water balance, SWAT model, Mundaú watershed

5.1 Introduction

In the last decades, around the world, there has been a severe change in the land use and consequently, modification in the hydrological and ecological behaviors (Khare et al., 2017). Generally, land use change has been carried by human activities (Sajikumar and Remya, 2015). Agriculture increase, deforestation, intensive grazing and urbanization are some examples of human activities that resulted in land use change (Worku et al., 2017).

In a watershed, alteration in land use is important because of its effect on the hydrological and ecological characteristics within the area. Land use change is one of the main causes of the surface runoff variation in a watershed, due to the alterations caused in the precipitation interception, evapotranspiration and soil hydraulic conductivity (Munoz-Villers and Mcdonnell, 2013; Yan et al., 2013). The quantity, intensity and velocity of runoff increased due to continuous increase in deforestation, agriculture and other anthropogenic practices (Booth 1991; Abbas et al. 2015).

Knowledge about the influence of land use change in a watershed play a fundamental role for the governments in order to articulate policy options to minimize its effects (Worku et al., 2017). In developing countries such as Brazil, whose economies are mostly dependent on agriculture and with rapid human population growth, land use changes are very common (Tufa, Abbulu and Srinivasarao, 2014). Deforestation – mainly the conversion of forest to agricultural land – has high rate both Brazil and Indonesia, which had the highest net loss of forest in the 1990s (FAO, 2010).

The Mundaú River Basin (MRB), which is a representative watershed of Brazilian Northeast, has experienced a lot of land use transformations over the years. The basin was originally formed by typical vegetation (Atlantic Forest and Caatinga), which was decreased over time, being replaced by pasture and agriculture, mainly sugarcane. The urban expansion was also one of the causes of the transformations that occurred in MRB.

In this context, supporting tools to study the impacts of land use change on water quantity and quality are essential to the implementation of policies and assist in the management of water resources. Researchers in various fields have required to improve and implement multiple instruments, including hydrological models, such as the Soil and Water Assessment Tool (SWAT) (Bressiani et al., 2015). The model was developed to analyze the impacts of land use changes on water runoff, sediment yield and water quality in large watersheds (Arnold et al., 1998). SWAT is a versatile model that considers different hydrological and agronomic components and has been applied by many governmental and private institutions, as well as universities and other institutions interested in supporting decision-making in the management of water resources (Bressiani et al., 2015).

In Brazil and in the world, several studies have been developed with the objective of verifying the effects of the land use changes on the runoff (Pereira et al., 2016; Zhang et al., 2016; Kundu et al., 2017; Marhaento et al., 2017) and sediment yield (Anaba et al., 2017; Blainski et al., 2017; Worku, Khare and Tripathi, 2017).

In this context, the aim of the study is assessing the issue of land use change and its effect on evapotranspiration, surface runoff and sediment yield of the study watershed.

5.2 Material and Methods

5.2.1 Study area

The area of the Mundaú River Basin (MRB) extends over 4,090.39 km² and ranges between southern latitude 8°42’–9°36’ and western longitude 35°47’–36°39’ (see Figure 1), with 52.2% of the area present in the State of Pernambuco, where is the upstream, and 47.8% in Alagoas, where is the downstream (APAC, 2015). The main economic activity in this basin is agriculture and livestock, which is maintained by the water availability within the watershed.

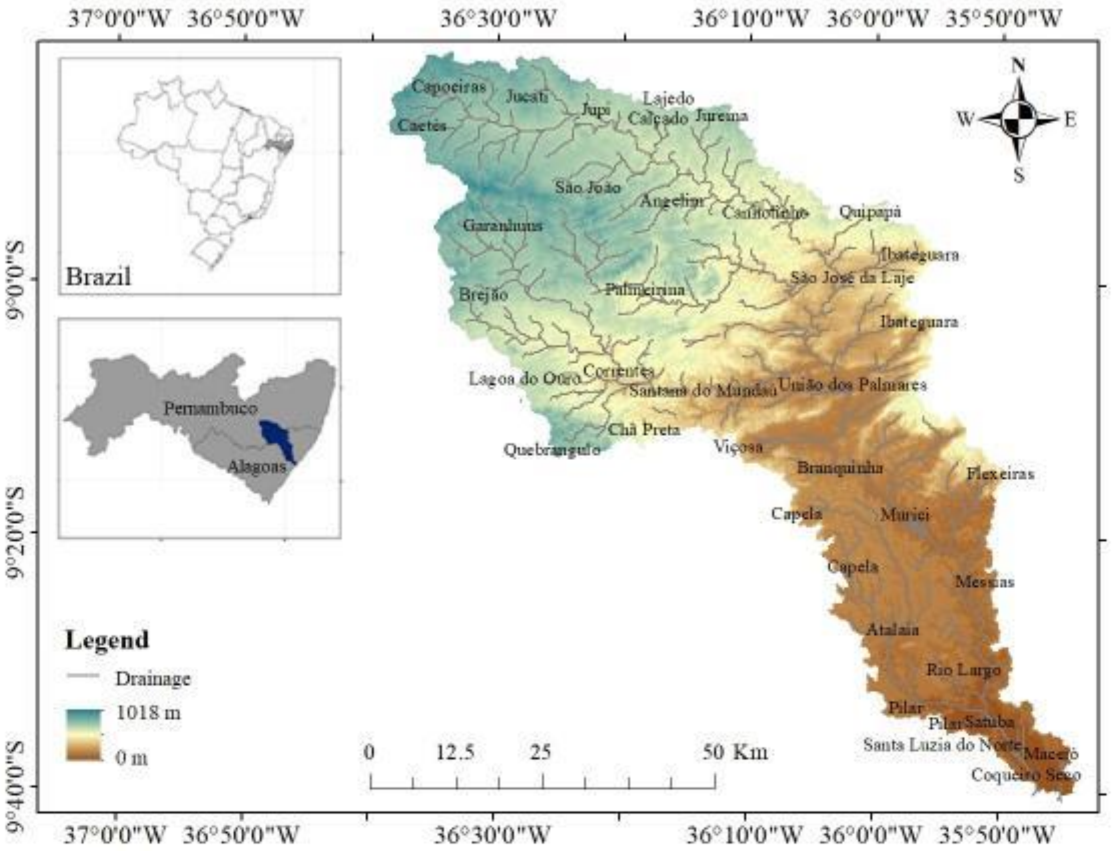


Fig. 1. Location map of the Mundaú River Basin (MRB) and their municipalities

The MRB is predominantly rural, has substantial agricultural activity, including, a large dairy and broilers breeding industry. It also has substantial sugarcane production and processing industry. The MRB also has areas of Caatinga vegetation, characterized by seasonally dry shrubs and forests (Leal et al., 2005), as well as Atlantic Forest vegetation, characterized by seasonally dry and tropical forests (Werneck, 2011). Mangroves and coastal vegetation are also found in the region.

The drainage area of the basin involves 34 municipalities, with part or all of the territory included in the basin, being 19 municipalities in the state of Alagoas and 15 municipalities in the state of Pernambuco. According to Pernambuco State Agency for Water and Climate (APAC), the municipalities Angelim, Correntes, Palmerina and São João are totally inserted in the basin. The municipalities of Brejão, Calçado, Capoeiras, Jucati, Jurema, Jupi and Lajedo are partially inserted in the basin. In Alagoas, the municipalities of Murici, União dos Palmares, São José da Laje, Santana do Mundaú, Satuba and Branquinha have a part in the basin.

The climate, according to the classification of Köppen, is Aw (Tropical, with dry season in winter). Most of the MRB is classified, in relation to amount of rainfall, as semi-humid and a small portion classified as semiarid, with an average temperature of 24 ºC. The average annual rainfall in the MRB is of 800 mm (Alvares et al., 2014), with precipitation declining as the distance from the coast increases.

The basin has great relevance because it presents high hydrological variability. There were episodes of peaks flows with flood problems, such as that in Santana do Mundaú, Alagoas, in 2010, causing damage in several areas. The basin also has experienced severe droughts, since part of it is already in the semiarid portion of Pernambuco, such as the recent exceptional drought of 2012, the highest of the last 50 years.

5.2.2 Hydrological modeling

The Soil and Water Assessment Tool (SWAT), freely available at (http://swat.tamu.edu/), is physically based and semi-distributed, continuous time, hydrological, long-term simulation model developed by United States Department of Agriculture Research Service (Arnold et al. 1998). The hydrological cycle in SWAT is based on the water balance equation (Eq. 1):

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(P - Q_s - ET - W_s - Q_{gw}\right) \tag{1}$$

Where: SW_t is the final soil water content in time t (mm) and SW_0 is the initial soil water content in time t (mm); t is time (days), P is precipitation in time t (mm), Q_s is surface runoff in time t (mm), ET is the actual evapotranspiration in time t (mm), W_s is percolation in time t (mm) and Q_{gw} is the baseflow in time t (mm) (Neitsch et al., 2005).

The conceptual framework of SWAT model and its setup is shown in Figure 2. The SWAT model requires four main types of input data, including three maps and one data series

(Step 1). The collection of all data used for hydrological modeling from different sources were performed in a previous study (see chapter 4). The digital elevation model (DEM) was obtained from the Shuttle Radar Topography Mission (SRTM), available at Brazilian Agricultural Research Corporation (EMBRAPA) Satellite Monitoring, where archives are available on the altimetry of Brazil. The land use map of the MRB was constructed using satellite images and image processing tools from LANDSAT 5 and 8, obtained from the National Institute of Space Research (INPE). The soil types map was obtained from data provided by the EMBRAPA, based on the information provided by the Agroecological Zoning of Pernambuco (ZAPE) and Alagoas (ZAAL), which provides maps in the scale of 1: 100,000. The hydrological data were obtained from the National Water Agency (ANA) and the Pernambuco State Agency for Water and Climate (APAC). The complete daily weather data series were obtained from the National Institute of Meteorology (INMET), using weather stations located in the cities of Garanhuns and Maceió. More information can be found in the chapter 4.

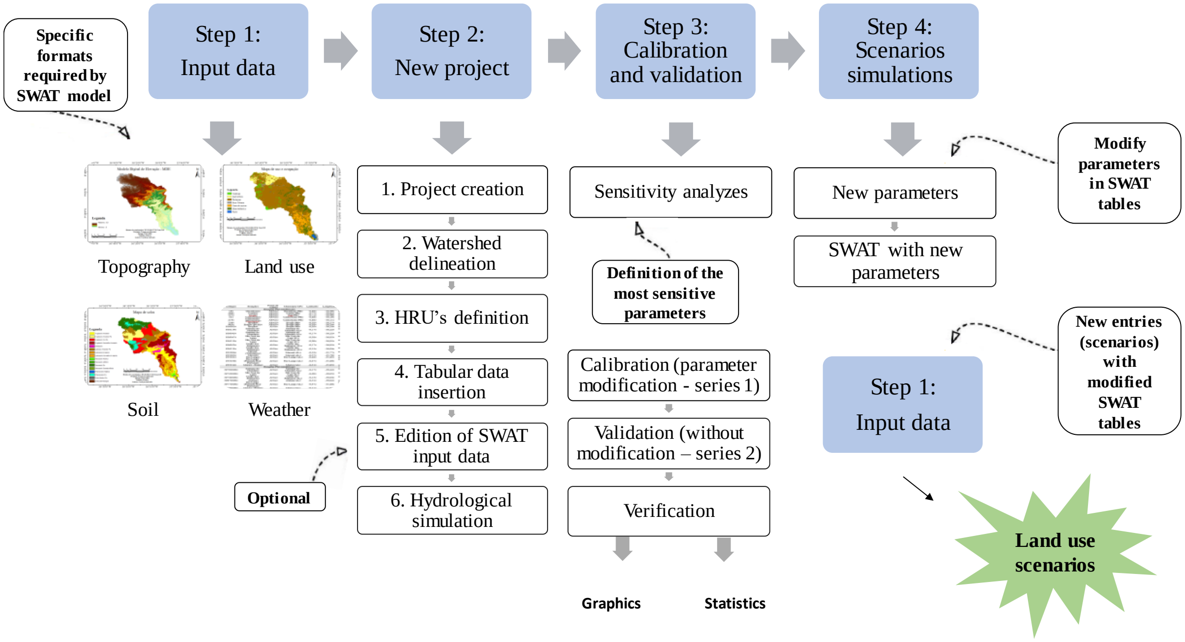


Fig. 2. Conceptual framework of SWAT model and its setup

In step 2 all input data is entered into the SWAT model. The model is coupled to the Geographic Information System (GIS). After the creation of the project, the first data to be inserted in the model is the DEM, to delimit the drainage network and the watershed (Watershed Delineation). The SWAT must be configured to delineate sub-basins with defined areas, and then generate the Hydrological Response Units (HRU's). For the division of the sub-basins, the SWAT is based on the concept of area necessary for the formation of a water course. On the other hand, the subdivision in HRU's is made from similar characteristics of soil use, soil type and slope found in an area, in this way, HRU's have homogeneous properties. The calculations of the variables are done separately in each HRU, in order to be summed and represent each sub-basin (Silva, 2014). With the generation of the HRU's, tabular data are entered with the series of precipitation data and other meteorological data. After this phase, the input data can be edited in order to improve the characterization of the study area. After these steps, the simulation with the model can be performed.

The results of SWAT are evapotranspiration, percolation, interception, water storage and surface runoff, which should be calibrated and validated. The calibration and validation procedures of the MRB (Step 3) was performed previously in the chapter 4 using the SWAT-CUP. The SWATCUP is an independent software developed for uncertainty and sensitivity analyses, calibration and validation processes, based on SWAT simulations. The program contains 5 calibration procedures, 11 objective functions and includes applications such as visualization of the study area (Abbaspour et al., 2007). The results related to the performance of the model and its statistical indices can also be verified in in the chapter 4.

Once calibrated and validated, the model can be used to simulate scenarios of land use changes (Step 4), which is exactly the focus of this study: verify the impact of land use changes dynamics on evapotranspiration, surface runoff and sediment yield. To do this, the values of the calibrated parameters of the final result generated in the SWAT-CUP must be transferred to SWAT model. With the modified values, the whole process described from stage 1 is done again, considering now the changes that occurred under the different scenarios adopted for evaluation.

5.2.3 Land use scenarios

The source for the land use data for the years 1987 and 2017 was generated from downloaded Landsat 5 and 8 imageries from http://www.dgi.inpe.br/CDSR/. The details of Landsat data are presented in Table 1. Initially, the images were converted into Universal Transfer Mercator and geo-referenced to a datum in which Brazil has been selected by WGS 84.

Table 1. Sources of Landsat images

N.	Images	Resolution (m)	Sensor	Path	Row	Year	Source
1	Landsat 5	30 x 30 m	TM	214 214 215	66 67 66	1987	http://www.dgi.inpe.br/CDSR/
2	Landsat 8	30 x 30 m	OLI	214 214 215	66 67 66	2017	http://www.dgi.inpe.br/catalogo/

To classify Landsat images, supervised classification was done adopting the maximum likelihood classifier. Seven land use classes were identified: i) Water, ii) Urban Area, iii) Atlantic Forest, iv) Caatinga, v) Pasture, vi) Agriculture, and vii) Sugarcane.

For modeling runoff response to land use changes, two scenarios of land use were analyzed over a period of 30 years, which were: a regeneration scenario (referring to use in the year 1987) and another scenario of degradation (referring to use in the year 2017).

In relation to statistical analyzes, we performed boxplots and data on the mean annual evapotranspiration, surface runoff and sediment yield were subjected to analysis of variance (F test) and test of Tukey, for comparison of means at 0.05 level of significance.

5.3 Results and Discussion

5.3.1 Land use changes in the Mundaú River Basin

The proportion of land use dynamics and corresponding percentage shared during the regeneration (referring to use in the year 1987) and degradation (referring to use in the year 2017) scenarios has been presented in Figs. 3, 4 and in Table 2. The study watershed has a total area of about 4,090.39 km². When looking at Figure 3 and 4, it is clear that the forests – Atlantic Forest and Caatinga – were the most present types of land use in 1987, presenting 33.26 and 22.23% of area, respectively. Already for the year 2017 it is noticed that the highest percentage of land use is exclusively by pastures, with 64.21%.

It is confirmed that an increase of pasture and sugarcane has been observed in the area in the last years. From 1987 to 2017, the urban expansion was also one of the causes of transformations in the land use of MRB. With the development in agricultural products and practices, the areas of cultivation and also the activities of livestock have grown over time, as well as urban expansion. These modifications characterized large losses of native vegetation, destruction of part of large forests, for replacement by such activities. According to Silva (2002), there is a low percentage of forest occupation of the Atlantic Forest around the world due to indiscriminate deforestation, especially those that occurred in the 60's and 80's, which resulted in the destruction of important species of fauna and flora.

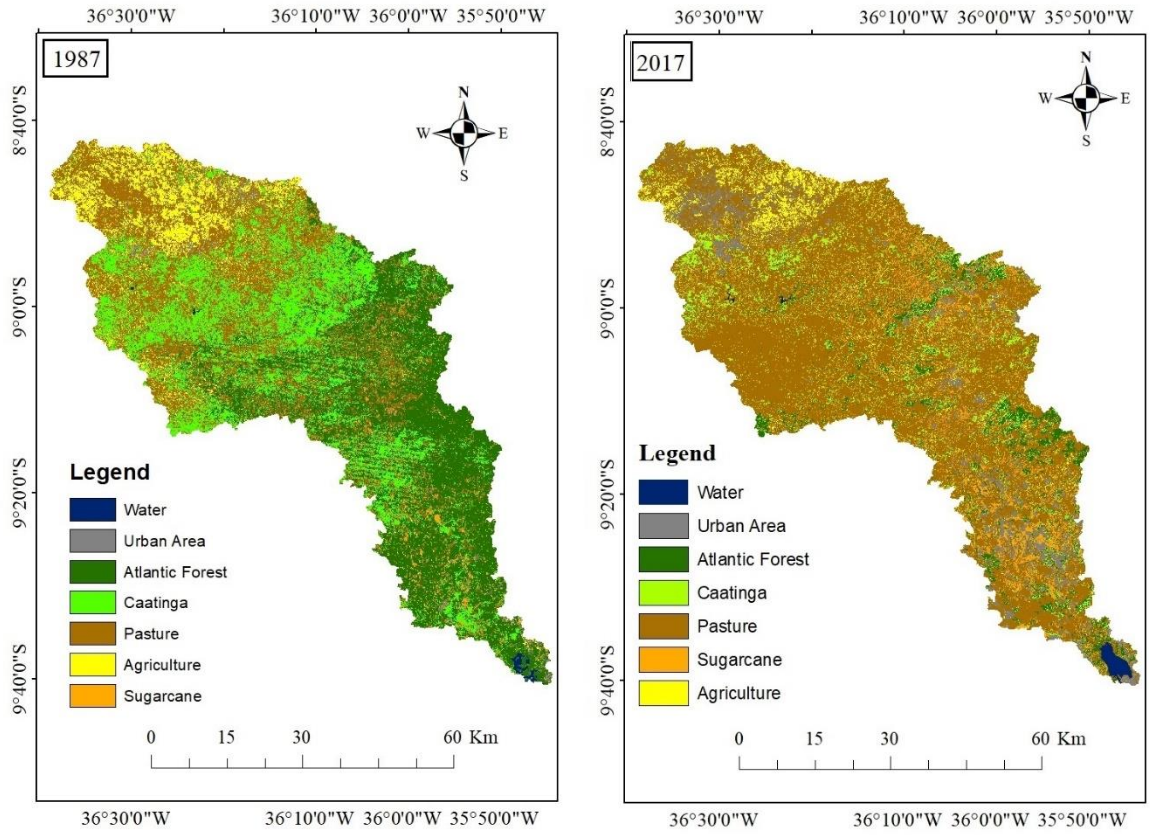


Fig. 3. Land use classes for Mundaú Basin in the regeneration (1987) and degradation (2017) scenarios

As can be seen in Fig. 3, the share of forest cover in the study watershed comprised of densely vegetated natural forest, plantation and shrubs in the regeneration scenario. According to Tucci and Clarke (1997) and Bruijnzeel (1996), forests have greater interception capacity than pastures. In this way, the direct evaporation of the intercepted water tends to be greater with the presence of native forest; processes such as infiltration and percolation of water in the soil also tend to increase. On the other hand, deforestation causes an increase in the average flow of a watershed, which can lead to problems such as extreme flood events. Such effects may become irreversible over the years, when there is intense agriculture and utilization of mechanization in the area.

Table 2. Land use areas in the regeneration (1987) and degradation (2017) scenarios of the Mundaú River Basin

Scenario	Regeneration (1987)		Degradation (2017)	
Land use	Area (km²)	Area (%)	Area (km²)	Area (%)
Water – WATR	10.5	0.3	26.8	0.7
Urban Area – URBN	146.4	3.6	343.6	8.3
Atlantic Forest – FRSE	1372.2	33.3	276.1	6.7
Caatinga – RNGB	917.4	22.2	264.0	6.4
Pasture – PAST	1223.4	29.7	2649.5	64.2
Sugarcane – SUGC	106.7	2.6	327.3	7.9
Agriculture – AGRL	349.4	8.5	238.8	5.8

Overall, during the last three decades (1987–2017), 1749.6 km² (76.4%) of forest were lost in the MRB. On the other hand, grazing land increased 1426.1 km², arriving in 2017 at little more than double the area that existed in 1987. The share of sugarcane land for the study watershed increased from 2.6% in 1987 to 7.9% during 2017. The urban portion also increased from 3.6% in 1987 to 8.3% during 2017. Generally, during the study periods the share of agricultural land it was more or less constant, with a slight reduction observed in 2017. The water bodies such as spring, streams ponds and small rivers accounted for the share of only 0.3% during 1987 and increased to 0.7% during 2017 (Table 2).

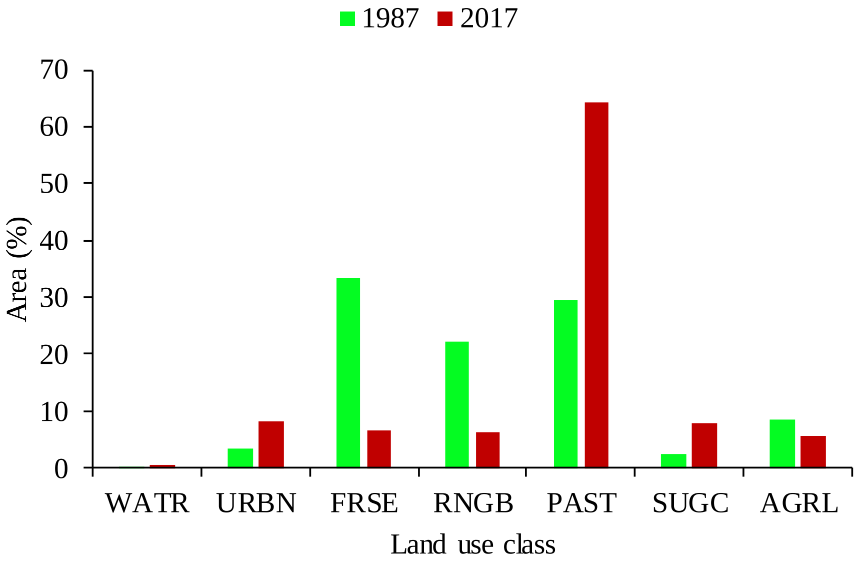


Fig. 4. Land use types and area coverage of Mundaú watershed in percentage from 1987 to 2017. WATR – Water, URBN – Urban area, FRSE – Atlantic forest, RNGB – Caatinga, PAST – Pasture, SUGC – Sugarcane, AGRL – Agriculture

The percentage change in land use class of Mundaú watershed from 1987 to 2017 is presented in Figure 5. The pasture increased by 34.6% from the regeneration to the degradation scenarios. According to Lima et al. (2012), pasture is a vegetation that have a few biomass and a shallow root system, and consequently, has a low evapotranspiration rate; such condition leads to an increase in the direct runoff (surface and subsurface) to the channels, increasing the annual mean flow in the watershed.

The net change in forest lands for the last 30 years (1987–2017) decreased by about 26.6% and 15.8% for Atlantic Forest and Caatinga, respectively. Marhaento et al. (2017) studying the changes in the water balance of the Samin catchment on Java, Indonesia using the SWAT model, found during the period 1994–2013, that deforestation by decreasing evergreen forest area and mixed garden area was about 30%. Additionally, settlements and agricultural areas increased by 25% and 6%, respectively. Rodrigues et al. (2015) evaluating the impact of changes in land use in the flow of the Pará River Basin, Brazil, found that from 1983 to 2012 there was an increase in the pastoralism, with 38% of the territory in 2012. The authors also observed that in this period, there was a reduction to approximately half the area originally occupied by the Atlantic Forest.

In the entire study period, there has been an increase in the sugarcane area by about 5.3% from the regeneration to the degradation scenarios. During the given time periods (1987–2017), urban area has increased to about 4.8% which took additional 197.2 km² from other land use categories. Another share of land use class for the study area is agriculture land, which was accounted 8.5% (349.5 km²) during 1987; in contrast, during 2017 it shrunk by about 2.7% (8.5–5.8%).

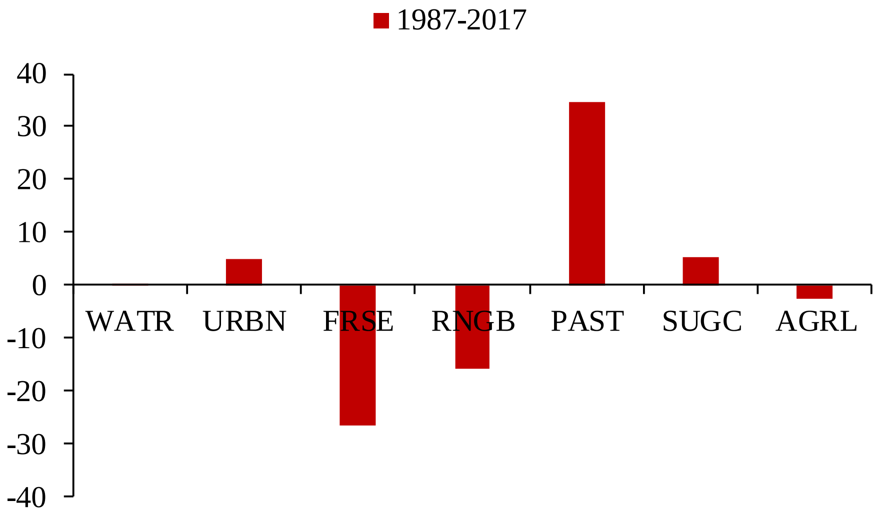


Fig. 5. Percentage change in land use class of Mundaú watershed from 1987 to 2017

5.3.2 Changes in water balance by following land use changes

The water balance of a watershed is a main constituent of water management and is influenced by several natural and anthropogenic issues. Modifications of water balance components caused by land use change, for example, can cause impacts to the environment, such as water stress in plants and extreme events such as droughts and floods (Kundu et al., 2017). Figure 6 shows the annual water balance in the Mundaú River Basin. The results reveal the magnitude of the impact of land use changes on water flow. Changes in land use over the years resulted in an increase of about 37% in water yield of the Mundaú River Basin, corresponding to 111.7 mm year^{-1}, in relation to the 1987. This increase in flow can be explained by reduction of the mean evapotranspiration of the basin from 726.9 mm in the 1987 to 603.2 mm in the 2017. Rodrigues et al. (2015) also found an increase in water flow and a decrease in ET in the Pará River Basin when the land use for 1983 was compared to the 2012 year. Kundu et al. (2017) analyzing the individual and combined impacts of future climate and land use changes on the water balance of the Narmada River Basin, India, found an increase water yield and decrease actual evapotranspiration (ET). The authors associated these results with the change in the Curve Number (CN) values, parameter used by SWAT to calculate surface runoff that considers, among other things, the changes that occur in land use. According to Pereira et al. (2016), the decrease in surface runoff is associated to the inferior values in the CN for the Atlantic Forest, since it allows greater protection to the soil surface and, consequently, better water infiltration.

Although the total aquifer recharge was higher in 2017, the percolation out of soil was also higher in this year, possibly indicating that losses were more pronounced when compared to 1987. The surface runoff was also a variable that presented higher values in 2017 when compared to 1987. This result affirms that a lower density of vegetation cover, and consequently, lower interception of precipitation by the canopy, causes an increase in surface runoff. This condition also leads to less water use by the soil, with the reduction of processes such as infiltration and percolation. Vegetal cover plays an essential role in the maintenance and balance of the hydrological cycle, performing functions in the control of water availability, which guarantee flow permanence (Rodrigues et al., 2015).

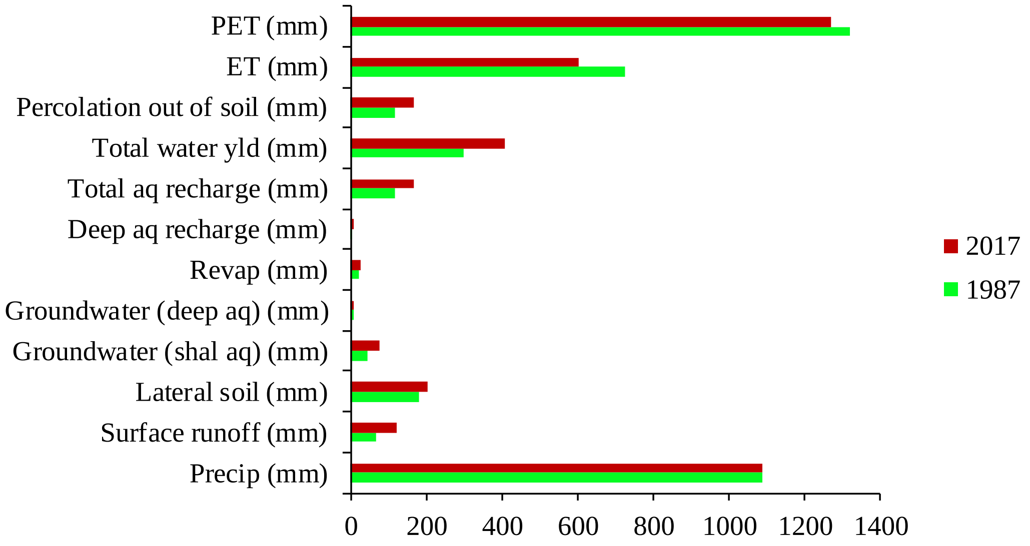


Fig. 6. Annual water balance due to land use change in the Mundaú River Basin

5.3.3 Effect of land use change on ET, surface runoff and sediment yield

Figure 7 shows the long-term changes in the ET, surface runoff and sediment yield for the regeneration and degradation scenarios. At the sub-catchment level, long-term trends were of growth for the superficial runoff and sediment production. To evapotranspiration, we found that there was a decrease over time, mainly due to the decrease of forest areas, as previously mentioned. As the Atlantic forest has higher values of leaf area index (LAI) when compared to pastures, gas exchange between the canopy and the environment is bigger (Pereira et al., 2010). Such condition allows an increase of the evapotranspiration. Furthermore, Atlantic Forest explores the soil more through its roots, which enables a greater water consumption by the plants. Marhaento et al. (2017) found that land use change due to deforestation and expansions of settlement area, reduced the mean annual ET and increased the mean annual streamflow in the studied watershed. According to authors, occurrences in the soil surface resulting in loss of organic matter cause a lower permeability and storage capacity (e.g. deforestation), leading to a decrease in the soil infiltration capacity. Thereby, much of the precipitation is converted into surface runoff.

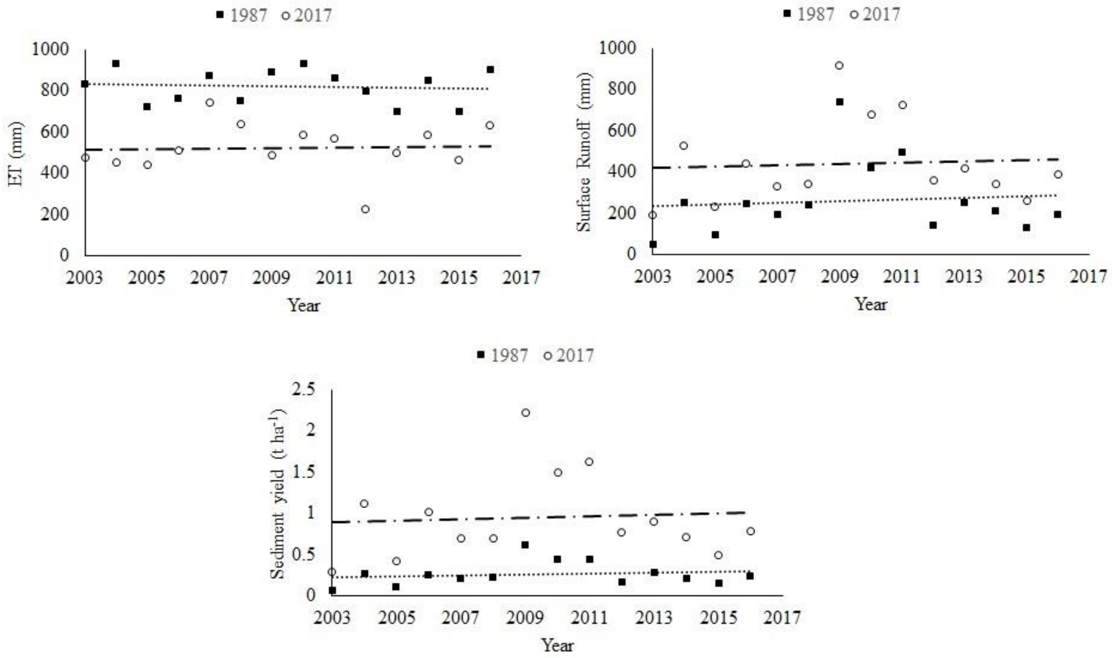


Fig. 7. Simulated ET, surface runoff and sediment yield including their long-term trend for the regeneration (1987) and degradation (2017) scenarios in the Mundaú River Basin

The amplitude and dispersion of data on simulated evapotranspiration, surface runoff and sediment yield in scenarios of 1987 and 2017 years in the Mundaú River Basin are show in Figure 8. From the obtained results by the SWAT model, it is possible to verify that between the years of 1987 and 2017 there was a decrease of the average values of evapotranspiration. Mean values and amplitudes of surface runoff and sediment yields were increasing over the years, mainly due to the decrease of the vegetation cover of the studied basin. Rodrigues et al. (2015) found highest mean flow and amplitude in 2012 when compared to 1983, due to the changes in land use and in the original plant cover of the Pará River Basin.

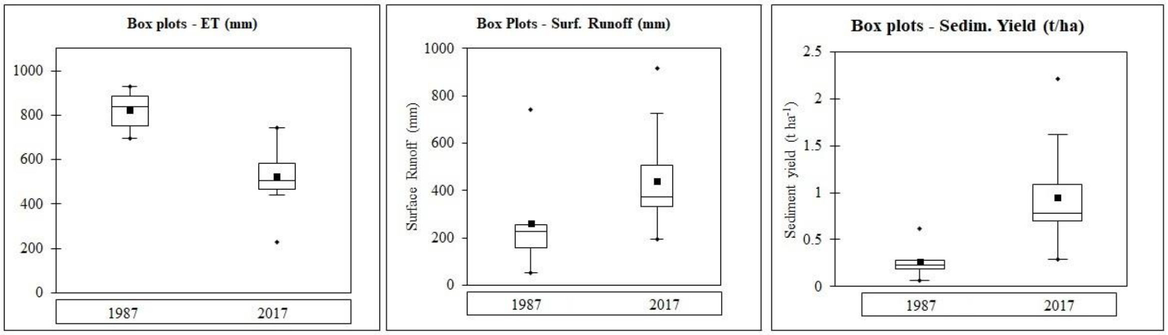


Fig. 8. Amplitude and dispersion of data on simulated evapotranspiration, surface runoff and sediment yield for the regeneration (1987) and degradation (2017) scenarios in the Mundaú River Basin

The Tukey's test statistic showed that there was significant difference between mean off all variables studied (evapotranspiration, surface runoff and sediment yield) for the two scenarios: 1987 and 2017 years (Table 3). These differences confirm the effect that changes in land use cause on the hydrological and sedimentological processes of a watershed. In MRB, there was a higher average value of evapotranspiration in 1987 when compared to 2017; and this fact can be explained by the higher density of vegetal cover existing in the 80's. Rodrigues et al. (2015) also found higher mean values of evapotranspiration in the original vegetation cover scenario when compared to current soil use.

Table 3. Statistical evaluation for mean evapotranspiration, surface runoff and sediment yield for the regeneration (1987) and degradation (2017) scenarios in the Mundaú Watershed

Variable	Scenario	
	Regeneration (1987)	Degradation (2017)
Precipitation (mm year^{-1})	1090.3	1090.3
Evapotranspiration (mm year^{-1})	820.8 A	522.25 B
Surface runoff (mm year^{-1})	263.3 A	440.6 B
Sediment yield (t ha^{-1})	0.265 A	0.947 B

Means followed by the same letter do not differ statistically by the Tukey test at the probability level of 0.05

The lower density of vegetation cover in 2017 may be one of the main causes of greater surface runoff and higher sediment yield in the Mundaú River Basin; these variables presented higher average values when compared with the 1987 values. Rodrigues et al. (2015) found higher average flow values in the current land use scenario when compared to the original vegetation cover. The surface runoff mean values ranged from 263.3 to 440.6 mm and the sediment yield mean values ranged from 0.265 to 0.947 t ha^{-1} between 1987 and 2017, respectively. According to Halecki, Kruk and Ryczeq (2018) there is a close relationship between surface runoff and erosion, that is, soil loss is affected by the intensity of water flowing through the soil surface. Additionally, according to the authors, water erosion is one of the main problems in agriculture.

According to the classification of soil erosion risk proposed by Marks et al. (1989), soil losses below 1 ton ha^{-1} year^{-1} do not present erosion risks. Values between 1 and 5 ton ha^{-1} year^{-1} are low risk. Thus, although MRB does not present a risk of erosion, changes in land use over the three decades have increased soil loss values to the acceptable limit of risk, since values above 1 ton ha^{-1} year^{-1} already present low risks of erosion. These results are a warning for the adoption of better management practices in MRB, to prevent negative effects on the ecosystem caused by erosion.

The total spatial effect of land use changes is considered in this study and three conditions over a period of 30 years are evaluated to get the view of water balance of the region with SWAT, particularly with the actual evapotranspiration (mm), surface runoff (mm) and total water yield (t ha^{-1}). According to Worku, Khare and Tripathi (2017) the complex nature of watershed, as well as spatial variation of different land use, can modify the water and sediment yields. Figure 9 shows the spatial distribution of the variables evapotranspiration, surface runoff and sediment yield for the regeneration and degradation scenarios. In fact, the regeneration scenario had higher values of evapotranspiration and lower values of runoff and sediment production, due to the higher density of vegetation cover when compared to the degradation scenario. On the other hand, surface runoff was higher in 2017 when compared to 1987; and it was probably for that reason that the sediment production also presented higher values in 2017 along the watershed. More specifically, land use changes particularly expansion of pasture and sugarcane areas may be responsible for significant increase in the surface runoff and sediment yield in the MRB. As already indicated in Fig. 6, the change in land use between 1987 and 2017 from forests into pasture and sugarcane areas has strongly contributed for increasing the surface runoff and sediment yield. Problems such as soil degradation, erosion, inadequate occupancy, are some examples that cause continuous changes in the land use of a watershed over time. In addition, processes such as construction of water catchment points, agricultural and urban expansions, deforestation, also contribute significantly to these changes (Worku, Khare and Tripathi, 2017).

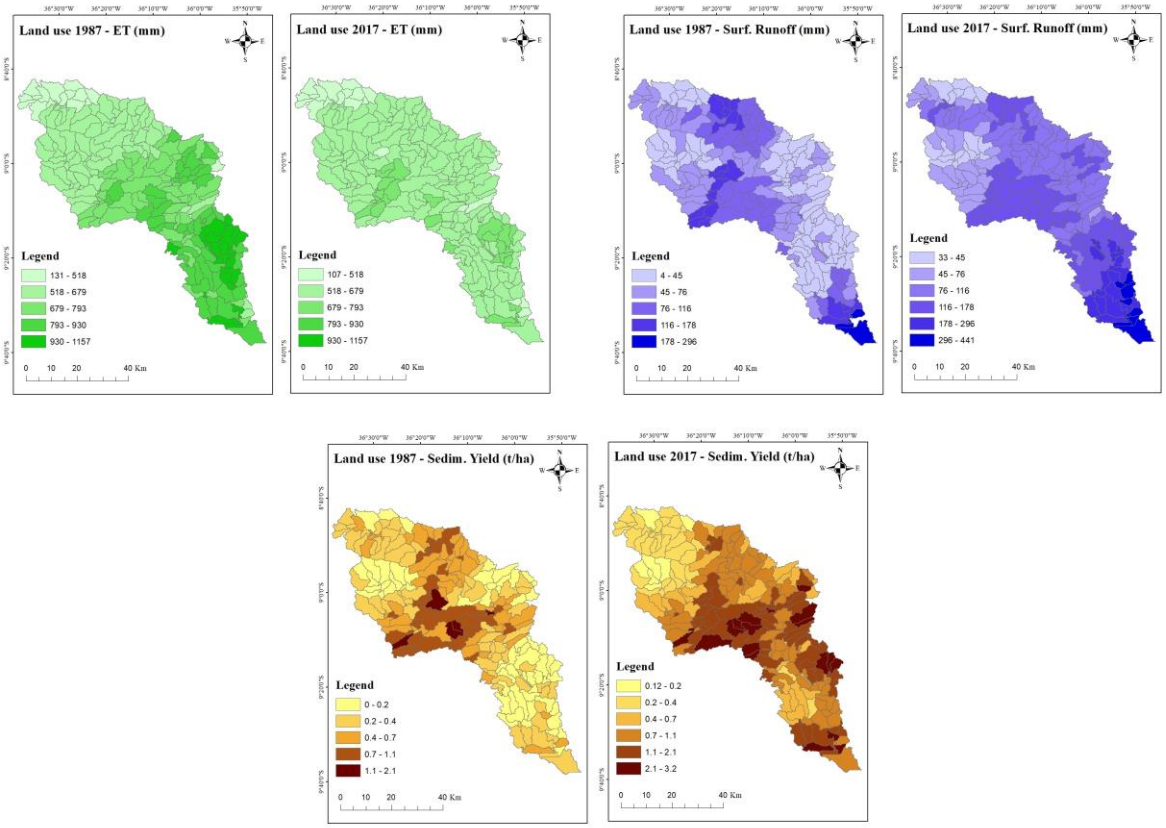


Fig. 9. Land use change impact on evapotranspiration (mm), surface runoff (mm) and sediment yield (t ha^{-1}) for the regeneration and degradation scenarios

According to Molina-Navarro et al. (2018) land use changes may cause uncertain consequences for water resources. The results achieved in this work confirm the indispensable role of vegetal cover in the maintenance of hydrological processes in a watershed (Tucci and Clarke, 1997). Such results can be adopted for decision-making related to the management of water resources in the area. Additionally, this research is applicable for similar watersheds, in order to understand the effects of land use change on water yield.

5.4 Conclusions

1. The analysis of results showed that the watershed experienced significant land use change between 1987 and 2017. This study confirmed that the majority of the land use occupied by forests in the Mundaú River Basin are reducing due to pasture and sugarcane expansion.

2. The main change in land use involved replacing the original vegetation by pasture in an area corresponding to 34% of the watershed.

3. Changes in land use over the regeneration and degradation scenarios have led to increased processes such as surface runoff and sediment yield. On the other hand, there was a reduction in the evapotranspiration. Hence, it can be concluded that spatial and temporal distribution of land use controls the water balance and sediment production in the Mundaú River Basin.

4. The SWAT model is an essential tool to simulate the spatial and temporal variability of evapotranspiration, surface runoff and sediment yield with following land use changes in the Mundaú watershed.

References

Abbas, T., Nabi, G., Boota, M.W., Hussain, F., Faisal, M., Ahsan, H., 2015. Impacts of land use changes on runoff generation in Simly watershed. Sci Int, 27, 4, 1.

Abbaspour, K.C., Yang, J., Maximov, I., Siber, R., Bogner, K., Mieleitner, J. Zobrist, J., Srinivasan, R., 2007. Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. Journal of Hydrology, 333, 413-430. http://doi.org/10.1016/j.jhydrol.2006.09.014.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M., Sparovek, G., 2014. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift, 22, 6, 711–728. https://doi.org/10.1127/0941-2948/2013/0507.

Anaba, L.A., Banadda, N., Kiggundu, N., Wanyama, J., Engel, B., Moriasi, D., 2017. Application of SWAT to assess the effects of land use change in the Murchison Bay Catchment in Uganda. Computational Water, Energy, and Environmental Engineering, 6, 24-40. http://doi.org/10.4236/cweee.2017.61003.

APAC, Agência Pernambucana de Águas e Clima (Pernambuco State Agency for Water and Climate) (www.apac.pe.gov.br). Accessed on: July 2015.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment part I: model development. Journal of the American Water Resources Association, 34, 73-89. http://dx.doi.org/10.1111/j.1752-1688.1998.

Blainski, E., Porras, E.A.A., Garbossa, L.H.P., Pinheiro, A., 2017. Simulation of land use scenarios in the Camboriú River Basin using the SWAT model. Brazilian Journal of Water Resources, 22, 33, 1-12. http://dx.doi.org/10.1590/2318-0331.011716110.

Booth, D.B., 1991. Urbanization and the natural drainage system–impacts, solutions, and prognoses. Northwest Environ J, 7, 1, 93–117.

Bressiani, D.A., Gassman, P.W., Fernandes, J.G., Garbossa, L.H.P., Srinivasan, R., Bonumá, N.B., Mendiondo, E.M., 2015. Review of Soil and Water Assessment Tool (SWAT) applications in Brazil: Challenges and prospects. International Journal of Agricultural and Biological Engineering, 8, 9-35. http://dx.doi.org/10.3965/j.ijabe.20150803.1765.

Bruijnzeel, L.A., 1996. Predicting the hydrological impacts of land cover transformation in the humid tropics: the need for integrated research. In: Gash, J. H. C., Nobre, C. A., Roberts, J. M., Victoria, R. L., 1996. Amazonian deforestation and climate. Chichester, Inglaterra: J. Wiley, Cap.2.

FAO, 2010. Global Forest Resources Assessment, Main report. Food and Agriculture Organization of the United Nations, FAO, Rome.

Halecki, W., Kruk, E., Ryczeq, M., 2018. Loss of topsoil and soil erosion by water in agricultural areas: A multicriteria approach for various land use scenarios in the Western Carpathians using a SWAT model. Land Use Policy, 73, 363–372. https://doi.org/10.1016/j.landusepol.2018.01.041.

Khare, D., Patra D., Mondal, A., Kundu, S., 2017. Impact of landuse/land cover change on runoff in the catchment of a hydro power project. Appl Water Sci, 7, 2, 23–35. https://doi.org/10.1007/s13201-015-0292-0.

Kundu, S., Khare, D., Mondal, A, 2017. Individual and combined impacts of future climate and land use changes on the water balance. Ecological Engineering, 105, 42-57. https://doi.org/10.1016/j.ecoleng.2017.04.061.

Leal, I.R., Silva, J.M.C., Tabarelli, M., Lacher Junior, T.E., 2005. Changing the course of biodiversity conservation in the Caatinga of northeastern Brazil. Conservation Biology, 19, 701-706. http://dx.doi.org/10.1111/j.1523-1739.2005.00703.x.

Lima,W.P., Laprovitera, R., Ferraz, S.F.B., Rodrigues, C.B., Silva; M.M., 2012. Forest and water consumption: A strategy for hydrosolidarity. International Journal of Forestry Research, 2012, 1-8. http://dx.doi.org/10.1155/2012/908465.

Marhaento, H., Booij, M.J., Rientjes, T.H.M., Hoekstra, A.Y., 2017. Attribution of changes in the water balance of a tropical catchment to land use change using the SWAT model. Hydrological Processes, 31, 2029-2040. http://dx.doi.org/10.1002/hyp.11167.

Marks, R., Müller, M.J., Leser, H., Klink, H.-J., 1989. Anleitung zur Bewertung des Leistungsvermögens des Landschaftshaushaltes (BA LVL) Zentralausschuß für deutsche Landeskunde. pp. 229 Forschungen zur Deutschen Landeskunde.

Molina-Navarro, E., Andersen, H.E., Nielsen, A., Thodsen, H., Trolle, D., 2018. Quantifying the combined effects of land use and climate changes on stream flow and nutrient loads: A modelling approach in the Odense Fjord catchment (Denmark). Science of the Total Environment, 621, 253–264. https://doi.org/10.1016/j.scitotenv.2017.11.251.

Munoz-Villers, L.E., Mcdonnell, J.J., 2013. Land use change effects on runoff generation in a humid tropical montane cloud forest region. Hydrological Earth System Science, 17, 3543–3560. https://doi.org/10.5194/hess-17-3543-2013.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2005. Soil and water assessment tool: Theoretical documentation version 2005. Temple: Blackland Research Center, 541p.

Pereira, D.R., Martinez, M.A., Silva, D.D., Pruski, F.F., 2016. Hydrological simulation in a basin of typical tropical climate and soil using the SWAT Model Part II: Simulation of hydrological variables and soil use scenarios. Journal of Hydrology: Regional Studies, 5, 149–163. http://dx.doi.org/10.1016/j.ejrh.2015.11.008.

Pereira, D.R., Mello, C.R., Silva, A.M., Yanagi, S.N.M., 2010. Evapotranspiration and estimation of aerodynamic and stomatal conductance in a fragment of Atlantic Forest in Mantiqueira range region, MG. Revista Cerne, 16, 32–40. http://dx.doi.org/10.1590/S0104-77602010000100004.

Rodrigues, E.L., Elmiro, M.A.T., Braga, F.A., Jacobi, C.M., Rossi, R.D., 2015. Impact of changes in land use in the flow of the Pará River Basin, MG. Revista Brasileira de Engenharia Agrícola e Ambiental, 19, 1, 70-76. http://dx.doi.org/10.1590/1807-1929/agriambi.v19n1p70-76.

Sajikumar, N., Remya, R.S., 2015. Impact of land cover and land use change on runoff characteristics. J Environ Manag, 161, 460–468. https://doi.org/10.1016/j.jenvman.2014.12.041.

Silva, C.A.I., 2014. Análise de aplicabilidade da interface do modelo hidrológico SWAT-SIG no estudo da produção de sedimentos em uma bacia no Nordeste do Brasil. Dissertation (Master in Water Resources and Sanitation) - Federal University of Alagoas, 53p.

Silva, L. F., 2002. 500 anos de uso do solo no Brasil. Editora Editus, Ilhéus, Ba. 2002. 605p.

Tucci, C. E. M., Clarke, R. T., 1997. Impacto das mudanças de cobertura vegetal no escoamento: Revisão. Revista Brasileira de Recursos Hídricos, 2, 135-152.

Tufa, D.F., Abbulu, Y., Srinivasarao, G.V.R., 2014. Watershed hydrological response to changes in land use/land covers patterns of river basin: A review. International Journal of Civil , Structural , Environmental and Infrastructure Engineering Research and Development (IJCSEIERD), 4, 157-170.

Werneck, F.P., 2011. The diversification of eastern South American open vegetation biomes: Historical biogeography and perspectives. Quaternary Science Reviews, 30, 1630-1648. https://dx.doi.org/10.1016/j.quascirev.2011.03.009.

Worku, T., Khare, D., Tripathi, S.K., 2017. Modeling runoff–sediment response to land use/land cover changes using integrated GIS and SWAT model in the Beressa watershed. Environ Earth Sci, 76, 550, 1-14. http://dx.doi.org/10.1007/s12665-017-6883-3.

Yan, B., Fang, N.F., Zhang, P.C., Shi, Z.H., 2013. Impacts of land use change on watershed streamflow and sediment yield: an assessment using hydrologic modelling and partial least squares regression. Journal of Hydrology, 484, 26–37. https://doi.org/10.1016/j.jhydrol.2013.01.008.

Zhang, L., Liu, Y., Wu, L., Cai, D., Ma, X., 2016. Impact of land-use scenarios on monthly runoff modeled by SWAT. Fresenius Environmental Bulletin, 25, 9, 3595-3605.

6. *Assessment of climate change impacts on water resources under RCP scenarios: A case study in the Mundaú River Basin, northeastern Brazil*

A version of this chapter was submitted to a peer-review international journal, with the following co-authors: Andrade, C.W.L., Montenegro, S.M.G.L., Montenegro A.A.A., Lima, J.R.S., Srinivasan, R. and Jones, C.A.

Abstract

Global climate predictions and possible impacts on the environment have caused great concern in society. Additional analyses of the impacts of climate change scenarios on regional hydrology are needed in order to design mitigation strategies for specific river basins. This study assessed the future climate change impacts on water resources of the Mundaú River Basin (MRB), in Brazil, using the Soil Water Assessment Tool (SWAT) and the Regional Climate Model (RCM) Eta-MIROC5 for three time periods under two Representative Concentration Pathways (RCPs). The Eta-MIROC5 model predicts that the MRB will experience significant precipitation decreases, between 0.4% and 25.3%, and maximum and minimum temperature increases between 1.0 and 0.9 ºC under the RCP 4.5 scenario and between 2.5 and 2.1 ºC under the RCP 8.5 scenario. The results of SWAT simulations predict substantial surface runoff decreases, with minimum value of 24.5 mm. Additionally, evapotranspiration (ET) is predicted to decrease from 780.77 to 652.8 mm. Annual and monthly streamflows are also predicted to decrease, more severely under the conditions of RCP 8.5. Seasonal streamflow is predicted to decrease, both in the rainy season (June, July and August) and in dry period (November, December and January). The findings of this study can assist water resource managers in decision making concerning the appropriate water use, creation of public policies that favor appropriate use, and adoption of mitigation and prevention practices to ensure water security in the basin.

Keywords: Hydrological simulation, SWAT model, CMIP5, Eta-MIROC5, Bias correction

6.1 Introduction

Climate change is recognized as one of the main 21st century environmental problems throughout the world (Vaghefi et al., 2017). Information related to global climate predictions and possible impacts on the environment has caused great concern in society. According to the National Water Agency of Brazil, forecasts are not optimistic, with predictions of greater water stress and social conflict due to the changes in water availability and impacts on the agricultural and other economic sectors, as well as with an increase in the frequency of extreme events.

Global warming due to increasing concentration of greenhouse gases may decrease water security (Yan et al., 2015), because this warming may cause substantial decreases in precipitation, surface runoff, evapotranspiration, and stream flows (Cuo et al., 2015; Haddeland et al., 2012; Pervez and Henebry, 2015; Zhang et al., 2010). Forecasts can predict an increase in air temperatures and a considerable decrease in precipitation (Estrela et al., 2012), causing changes in the hydrologic regime of watersheds (Arnell, 1999). Additionally, when these changes happen in areas with inadequate water availability and frequent extreme weather events, these impacts might be intensified (Senent-Aparicio et al., 2017).

The Coupled Model Intercomparison Project Phase 5 (CMIP5) developed four climate change scenarios, representing four radiative forcing target levels, called Representative Concentration Pathways (RCPs) for 2100: 2.6 W m^{-2} (very low forcing level), 4.5 and 6.0 W m^{-2} (medium stabilization scenarios), and 8.5 W m^{-2} (very high emission scenario) (Meinshausen et al., 2011; Taylor et al., 2012). These RCPs (RCP 2.6, RCP 4.5, RCP 6.0 and RCP8.5) have been applied in several studies involving emissions mitigation and analysis of climate change impacts (Van Vuuren et al., 2011).

Climate change impacts have been studied for the past three decades with simulations executed by General Circulation Models (GCMs) (Gonzalez et al., 2010; Jing et al., 2015). However, GCM spatial resolutions are frequently too coarse for regional impact studies on watersheds (Deb et al., 2014; IPCC, 2013; Wilby et al., 2002). According to Chou et al.

(2014a), studies of relationships between climate change and hydrological processes on the regional scale require more detailed data since the susceptibilities of a region to climate change are related to local conditions. In this context, Regional Climate Models (RCMs) might be an alternative to improve analyzes, since RCMs provide more detailed spatial data (Rajib and Rahman, 2012).

The Soil and Water Assessment Tool (SWAT), a physically based, semi-distributed, continuous-time, long-term and basin-scale hydrological model (Arnold et al. 1998) is a widely used tool for studying simulated hydrological and water quality responses to climate change around the world (Brouziyne et al., 2018; Carvalho-Santos et al., 2017; Ouyang et al., 2015; Senent-Aparicio et al., 2017; Shiferaw et al., 2018; Tan et al., 2017; Vaghefi et al., 2017; Zhang et al., 2016) as well as in Brazil (Oliveira et al., 2017; Sousa, 2017).

The objective of this study was to evaluate the future climate change impacts on water resources of the Mundaú River Basin (MRB), in Brazil. The specific objectives were to (1) assess the future climate changes under two Representative Concentration Pathways and three time periods, (2) quantify hydrological processes using the SWAT model for future climate scenarios, and (3) evaluate possible effects of climate changes on water resources for the future over the study area.

6.2 Material and Methods

6.2.1 Description of the study area

The area of the Mundaú River Basin (MRB) extends over 4,090.39 km² and ranges between southern latitude 8°42’–9°36’ and western longitude 35°47’–36°39’ (see Figure 1), with 52.2% of the area in the State of Pernambuco (upstream) and 47.8% in Alagoas (downstream) (APAC, 2015). The main economic activities in the basin are agriculture and livestock grazing, which are dependent on rainfall within the watershed.

The MRB is predominantly rural, has substantial agricultural activity, including, a large dairy and broiler industries. It also has substantial sugarcane production and processing. The MRB also has areas of Caatinga vegetation, characterized by seasonally dry shrubs and forests (Leal et al., 2005), as well as Atlantic Forest vegetation, characterized by seasonally dry and tropical forests (Werneck, 2011). Mangroves and coastal vegetation are also found in the region.

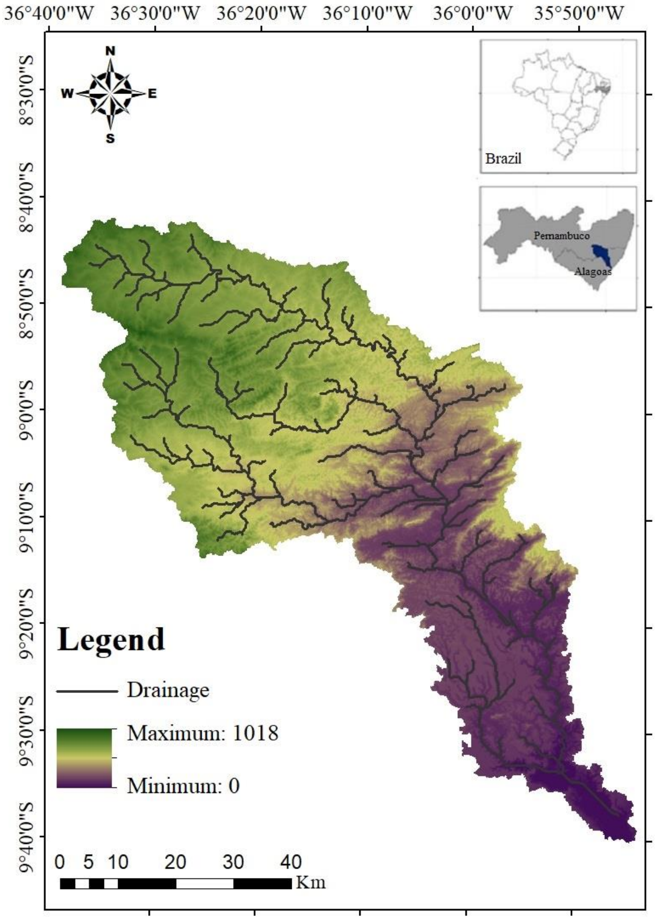


Fig. 1. Location map of the Mundaú River Basin (MRB)

The watershed includes all or part of 19 municipalities in Alagoas and 15 municipalities in Pernambuco. According to the Pernambuco State Agency for Water and Climate (APAC), the municipalities Angelim, Correntes, Palmerina and São João are totally within the basin. The municipalities of Brejão, Calçado, Capoeiras, Jucati, Jurema, Jupi and

Lajedo are partially within the basin. In Alagoas, the municipalities of Murici, União dos Palmares, São José da Laje, Santana do Mundaú, Satuba and Branquinha are partly within the basin.

The climate, according to the classification of Köppen, is Aw (Tropical, with dry season in winter). Most of the MRB is classified as semi-humid, and a small portion is semiarid, with an average temperature of 24 ºC. The average annual rainfall of the basin is 800 mm with historical annual values ranging from 497 to 1,143.63 mm for different years (Alvares et al., 2014; Araújo et al., 2015). In the coastal portion of the basin, rainfall can reach 2,000 mm due to the maritime influences (Gomes et al., 2016). Precipitation declining as the distance from the coast increases. The rainy season is in the months of March to June (Araújo et al., 2015).

The basin has large hydrological variability. Peaks flows can cause flooding, such as in Santana do Mundaú, Alagoas, in 2010. The basin also has experienced severe droughts, such as the recent exceptional drought of 2012, the worst in the last 50 years.

6.2.2 SWAT model

The Soil and Water Assessment Tool (SWAT), freely available at (http://swat.tamu.edu/), is physically based and semi-distributed, continuous-time, hydrological, long-term simulation model developed by United States Department of Agriculture Research Service (Arnold et al. 1998). The hydrological cycle in SWAT is based on the water balance equation (Eq. 1):

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(P - Q_s - ET - W_s - Q_{gw}\right) \qquad (1)$$

Where: SWt is the final soil water content in time t (mm) and SW_0 is the initial soil water content in time t (mm); t is time (days), P is precipitation in time t (mm), Q_s is surface runoff in time t (mm), ET is the actual evapotranspiration in time t (mm), W_s is percolation in time t (mm) and Q_{gw} is the baseflow in time t (mm) (Neitsch et al., 2005).

The SWAT model requires four main types of input data, including three maps and one data series. For this study, the digital elevation model (DEM) was obtained from the Shuttle Radar Topography Mission (SRTM), available at EMBRAPA Satellite Monitoring. The land use map of the MRB was constructed using satellite image from LANDSAT 5, obtained from the National Institute of Space Research (INPE). The soil types map was obtained from data provided by the Brazilian Agricultural Research Corporation (EMBRAPA), based on the information provided by the Agroecological Zoning of Pernambuco (ZAPE) and Alagoas (ZAAL), which provides maps in the scale of 1: 100,000. The hydrological data were obtained from the National Water Agency (ANA), the Pernambuco State Agency for Water and Climate (APAC) and the National Institute of Meteorology (INMET).

The model is coupled to the Geographic Information System (GIS). In this study, the ArcGis™ software version 10.1 (Enviromental Systems Research Institute – ESRI 1998) was used. After the creation of the project, the first data to be inserted in the model is the DEM, to delimit the drainage network and the watershed (Watershed Delineation). The SWAT must be configured to delineate sub-basins with defined areas, and then generate the Hydrological Response Units (HRU's). For the delineation of sub-basins, SWAT uses the concept of area necessary for the formation of a water course. HRUs are defined as areas with identical characteristics of weather, land use, soil type and slope. SWAT simulates all hydrologic and other process for each HRU, and the results for all HRUs within a sub-basin are summed to represent the hydrology and other processes within that sub-basin (Silva, 2014). The hydrological components of SWAT are evapotranspiration, infiltration and percolation, interception storage and surface runoff.

The calibration and validation procedures of the MRB were performed previously using SWAT-CUP for the baseline period (2003-2016). SWATCUP is an independent software developed for uncertainty and sensitivity analyses, calibration and validation of

SWAT simulations. The program contains five calibration procedures, eleven objective functions and includes applications such as visualization of the study area (Abbaspour et al., 2007).

Once calibrated and validated, the model may be used to simulate climate changes scenarios, which is exactly the focus of this study: to evaluate the future climate change impacts on water resources of the Mundaú River Basin (MRB). To do this, the calibrated parameters values of the final result generated in the SWAT-CUP must be transferred to SWAT model.

6.2.3 Future climate change scenarios

General Circulation Models (GCMs) are complex global-scale models of physical processes, and their resolutions are generally too coarse to be useful for assessment of the future climate changes at local scales, for example, impacts on the watersheds. Within this context, Regional Climate Models (RCMs) associated to GCMs may be used to provide data at scales appropriate for local impact studies (Chou et al., 2014b).

In order to project the possible future impacts on hydrological processes due to climate change in the MRB, simulated scenarios from the General Circulation Model (GCM) MIROC5, dynamically downscaled by the RCM Eta (Chou et al., 2014b), were used in this study. The Eta-MIROC5 (Watanabe et al., 2010) is an ocean–atmosphere model with resolution of about 150 km in horizontal and 40 km in vertical, which was created through Japanese-Brazilian cooperation. The Eta-MIROC5 has been made available (https://projeta.cptec.inpe.br/#/dashboard) by the Brazilian National Institute of Spatial Research (INPE/CPTEC) and previously been applied for future climate change impacts studies with the SWAT model in Brazil (Oliveira et al., 2017). The RCM Eta outputs include daily rainfall, minimum and maximum temperature, among others variables. In our study, the forecast data were divided into three periods – short term (2017 to 2040), medium term (2041 to 2070) and long term (2071 to 2099) – and compared with the baseline period (2003 to 2016). Therefore, the effects of changes in precipitation and minimum and maximum temperatures for future periods were assessed.

The Eta-MIROC5 was simulated based on two different Representative Concentration Pathways (RCPs) of the CMIP5: RCP 4.5 and RCP 8.5. These RCPs are based on assumed natural and anthropogenic radiative forcing through the end of the 21st century. They characterize the change in input and output radiation to the atmosphere produced by modifications in atmospheric elements, such as carbon dioxide (Moss et al., 2010). The RCP 4.5 scenario indicates a medium forcing level (realistic emission), with a stabilization of 4.5 W m^{-2} before 2100 resulting from policies and technologies designed to minimize the emission of greenhouse gases; moreover, this RCP represents a global average warming ranging from 1.1 to 2.6 °C (IPCC, 2013). The RCP 8.5 is a very high greenhouse gases emission scenario (pessimistic emission), with an increase in radiative force of 8.5 W m^{-2} by 2100 (Tan et al., 2017); this RCP corresponds to a global average warming ranging from 2.6 to 4.8 °C (IPCC, 2013). An overview of the representative concentration pathways, including these two scenarios, were detailed by van Vuuren et al. (2011).

6.2.4 Statistical bias correction method

It is well known that outputs from GCMs and RCMs – such as precipitation and temperatures data – generally contain systematic errors (biases) and cannot be used directly in hydrological modelling, since they can generate significant deviations between simulated and observed data (Chen et al., 2016; Oliveira et al., 2017). Therefore, for studies that involve the evaluation of the impacts of climate change on hydrological processes, it is strongly recommended to carry out biases correction of GCM/ RCM forecast data (Graham et al., 2007; Teutschbein and Seibert, 2010). Bias correction is usually adopted to reduce differences and uncertainty between simulated and observed data using empirical relationships; such correction might be applied from local conditions to large scales (Piani et al., 2009).

Rathjens et al. (2016) created Climate Model for Hydrologic Modeling (CMhyd) to perform bias correction of precipitation and temperature data from several climate models. This program extracts and bias corrects precipitation and temperature data from global and regional climate models, and provides eight approaches of bias correction, including linear scaling, delta change, local intensity scaling, power transformation, variance scale and distribution mapping. In this study, Linear Scaling (LS) was applied to bias correct downscaled precipitation and temperature data. This technique was chosen after reviewing the study of Teutschbein and Seibert (2010), which evaluated five bias correction methods for precipitation and four bias correction techniques for temperature, and according to the authors, linear scaling is suitable both for precipitation and temperature. This approach works with monthly correction values established on the differences between observed and historical simulated data (Teutschbein and Seibert, 2010; Oliveira et al., 2017). This technique uses the equations below:

$$P^{*}{}_{contr}(d) = P_{contr}(d).\left[\frac{\mu_m(P_{obs}(d))}{\mu_m(P_{contr}(d))}\right] \tag{2}$$

$$P^{*}{}_{scen}(d) = P_{scen}(d).\left[\frac{\mu_m(P_{obs}(d))}{\mu_m(P_{contr}(d))}\right] \tag{3}$$

$$T^{*}{}_{contr}(d) = T_{contr}(d) + \mu_m(T_{obs}(d)) - \mu_m(T_{contr}(d)) \tag{4}$$

$$T^{*}{}_{scen}(d) = T_{scen}(d) + \mu_m(T_{obs}(d)) - \mu_m(T_{contr}(d)) \tag{5}$$

where P(d) and T(d) are daily precipitation and temperatures, respectively; μm is the mean of the variable m within the month; and ‘contr’, ‘scen’ and ‘obs’ refer to the control (baseline period), scenarios and observed data, respectively.

In the LS approach, bias-corrected simulation data will agree, in their monthly average values, with the observed data. Precipitation and temperature variables are adjusted with a factor based on the ratio of long-term monthly average observed and control run data.

These factors are expected to continue unvaried under future conditions (Lenderink et al., 2007; Teutschbein and Seibert, 2012).

The period used for the application of the linear scaling method for the bias correction of future data (2017 to 2099) was from 1980 to 2005 (bias baseline), in which the observed precipitation data comprised eleven stations and the temperature data, two stations, distributed throughout the MRB. The simulated historical data corresponding to the same period came from the historical series of the Eta-MIROC5 model. The conceptual framework of the bias correction for historical and future RCMs are presented in Figure 2.

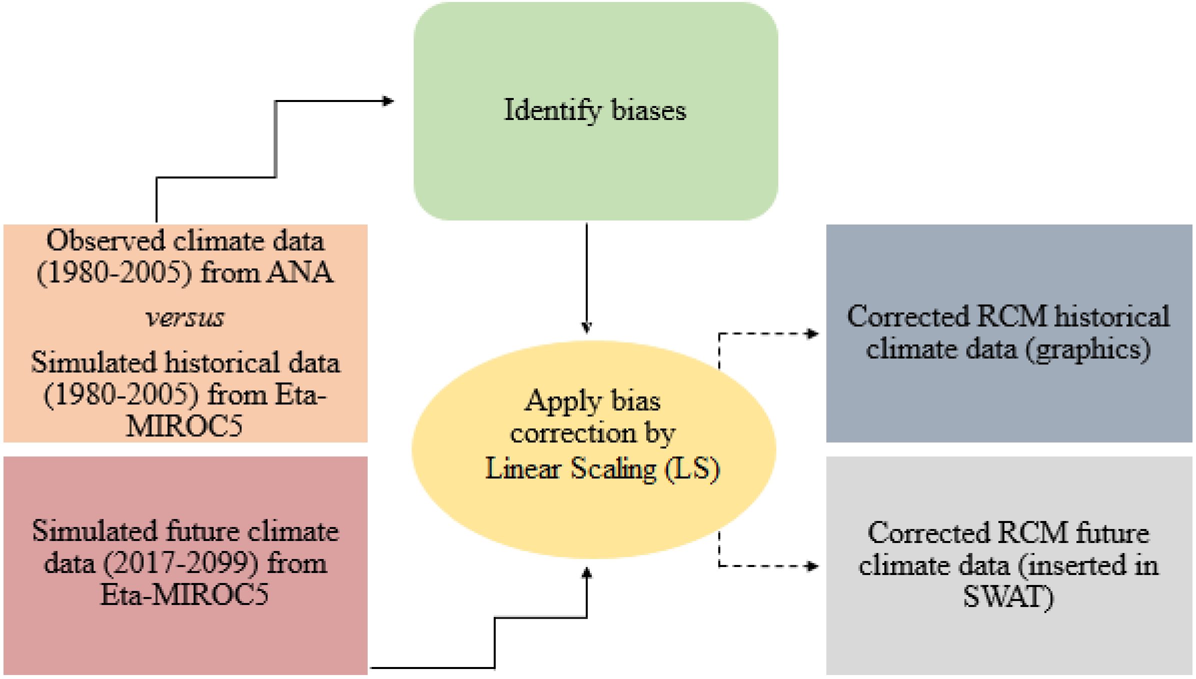


Fig. 2. Bias correction flow chart for historical and future RCM (adapted from Vaghefi et al., 2017)

6.2.5 Assessment of climate change impacts on water resources

To assess the climate change impacts on water resources in the MRB, the SWAT model was calibrated for the baseline conditions (2003 to 2016) and then, applied in the present study, for the simulation of climate change scenarios. After performing the bias correction of the Eta-MIROC5 future projections data, the water balance components (surface runoff, evapotranspiration and groundwater recharge) simulated by SWAT model from the baseline period (2003–2016) were compared to the results of the three future time periods (2017–2040, 2041–2070 and 2071–2099) under the RCPs (RCP 4.5 and RCP 8.5).

6.3 Results and Discussion

6.3.1 Bias correction by Linear Scaling approach

The graphs related to bias correction of the data (1980-2005) projected by the Eta-MIROC5 model by the Linear Scaling method are presented in Figures 3 and 4. In total, data were corrected from 11 rainfall stations and two stations of maximum and minimum temperatures within the MRB. It can be noted from the graphs that the LS method suitably corrected the raw historical data of the Eta-MIROC5 model (1980-2005). This approach has been demonstrated to be effective for the study of precipitation data in previous works (Block et al., 2009; Piani et al., 2010; Teutschbein and Seibert, 2012). Bias correction produced an increase in both mean maximum and minimum temperatures for the two stations, corroborating with the results found by Oliveira et al. (2017), when evaluating the climate change impacts on streamflow and hydropower potential in the headwater region of the Grande River Basin in southeastern Brazil.

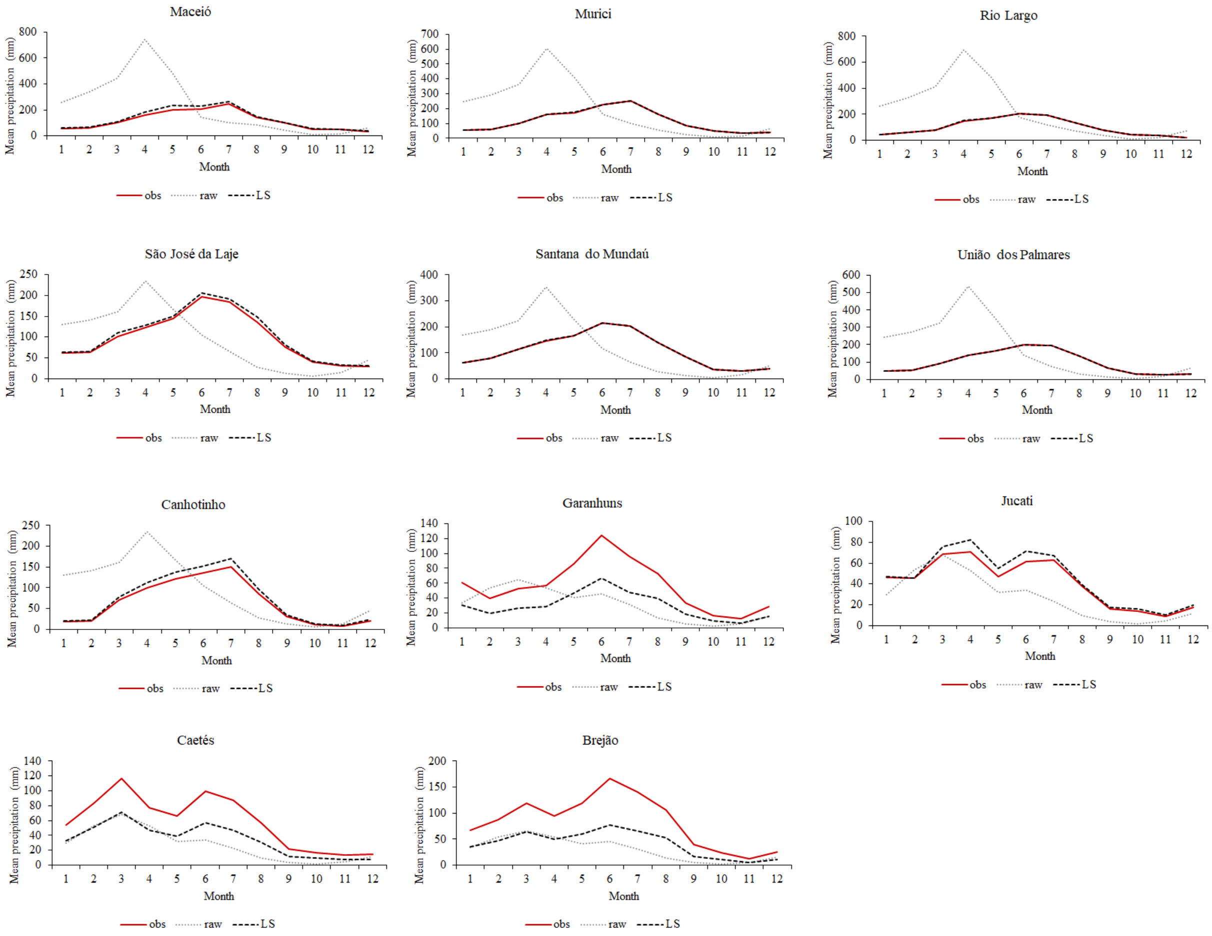


Fig. 3. Bias correction by the Linear Scaling method using CMHyd software for precipitation gauges in the MRB (obs = observed historical data (1980-2005); raw = raw historical data (1980-2005); LS = corrected historical data (1980-2005) by Linear Scaling method)

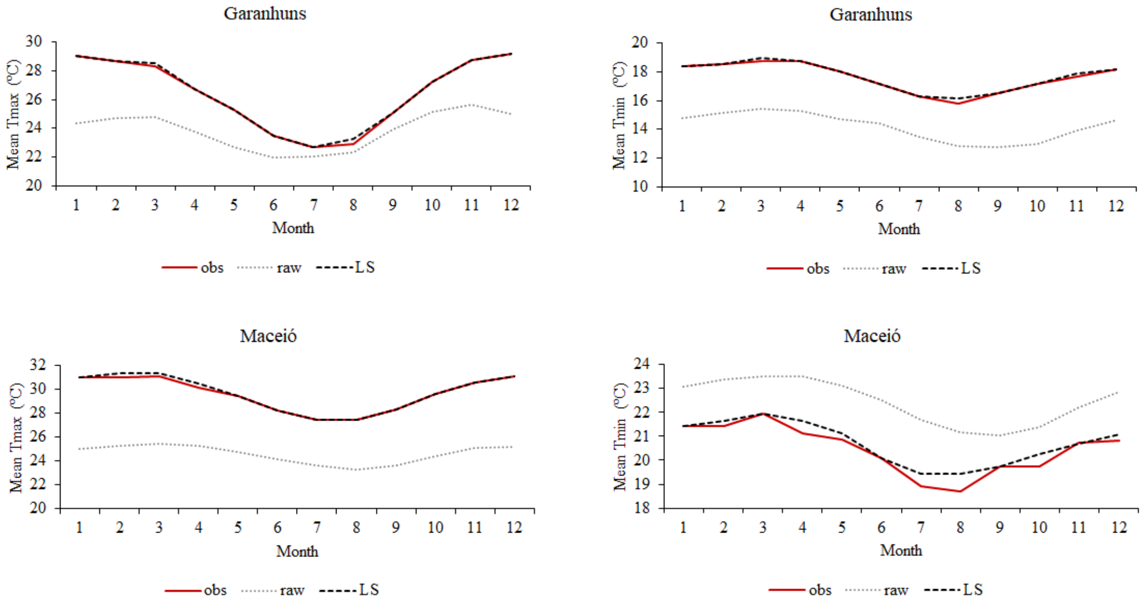


Fig. 4. Bias correction by the Linear Scaling method using CMHyd software for temperature gauges in the MRB (obs = observed historical data (1980-2005); raw = raw historical data (1980-2005); LS = corrected historical data (1980-2005) by Linear Scaling method)

Evaluating the standard deviation through the study period offers information about the efficiency of bias correction and uncertainty control (Brouziyne et al., 2018). For the bias corrections made at the 11 rainfall stations, average standard deviation values from 0 to 17.4 mm were observed. For maximum and minimum temperatures, average standard deviation values were between 0.4 and 1.6 ºC. Brouziyne et al. (2018) modeling sustainable adaptation strategies in a Mediterranean watershed under projected climate change scenarios, also found lower standard deviation values for temperature and precipitation using the linear scaling method.

6.3.2 Future climate in the MRB: precipitation and temperature changes

Corrected projections for annual precipitation and temperatures from the Eta-MIROC5 RCM for the three future time periods under the RCPs are summarized in the Table

1. The results indicate that the MRB will certainly experience less rainfall and greater temperatures in the future for both emission scenarios. The average projected rainfall decreased in all three periods, ranging from 1087.45 mm in short term to 939.69 mm in medium term under RCP 4.5. Under RCP 8.5, precipitation is projected to decrease to 1041.07 mm in the short term and 815.59 mm in the long term. These decreases represent, from short term to medium and long term, approximately 13.6% in the RCP 4.5 scenario and 21.7% in the RCP 8.5 scenario. Ouyang et al. (2015), assessing the impacts of climate change under RCP scenarios on streamflow in the Huangnizhuang catchment also found precipitation decreases in 2011-2040 period under three RCPs studied (RCP 2.6, RCP 4.5 and RCP 8.5).

Table 1. Precipitation and temperature from the Eta-MIROC5 RCM for the three future time periods under the RCPs

Period	RCP 4.5			RCP 8.5		
	Prec	Tmax	Tmin	Prec	Tmax	Tmin
Short term (2017-2040)	1087.45	28.73	19.91	1041.07	28.67	19.93
Medium term (2041-2070)	939.69	29.58	20.55	839.38	30.02	20.93
Long term (2071-2099)	1014.23	29.69	20.84	815.59	31.17	22.00

Prec – precipitation (mm), Tmax – maximum temperature (ºC), Tmin – minimum temperature (ºC)

In relation to temperature, the maximum temperatures projected for the short term at 28.7 under both RCPs will reach until 29.7 and 31.2 °C in the long term, under both RCPs 4.5 and 8.5, respectively. This represents an increase of 1.0 ºC under the RCP 4.5 scenario and 2.5 ºC under the RCP 8.5 scenario. The minimum temperatures of 19.9 ºC under both RCPs, in the short term, will become 20.8 and 22.0 ºC, under the RCPs 4.5 and 8.5, respectively, in the long term. These results represent increments in the minimum temperatures of 0.9 and 2.1 ºC for RCPs. Ouyang et al. (2015) found increase in maximum and minimum temperatures over time. The maximum increment found were 4.1 °C and 3.8 °C for the period 2071-2100 under RCP 8.5 for the maximum and minimum temperatures, respectively. It is very important to study the temperature variations, since, according to the authors, this variable is closely related to the processes of evapotranspiration and streamflow in a watershed. Oliveira et al. (2017) found an average increase of 1.4 and 1.2 °C for maximum and minimum temperatures for RCP 4.5 and 2.2 °C for both maximum and minimum temperatures for RCP 8.5 in relation to the baseline period. According to the authors, this greater warming in the RCP 8.5 was expected, since in this scenario there are higher concentrations of carbon dioxide (CO_2). Shiferaw et al. (2018), studying the hydrological response under climate change scenarios in the Ilala watershed, Northern Ethiopia, found the highest minimum and maximum temperatures during the end-term period (2070-2099) under RCP 8.5, which were predicted by the "HadGEMs-ES" model. Zhang et al. (2016), verified the impacts of climate change on streamflow under RCP scenarios in Xin River Basin, China, and found increases in maximum and minimum temperatures under the three RCPs analyzed (RCP 2.6, 4.5 and 8.5) at the end of the 21st century, especially under RCP 8.5 conditions.

Future changes in annual rainfall, maximum and minimum temperature at the MRB under two RCP scenarios for the short term, medium term and long term periods are shown in Figure 5. The annual precipitation could decrease 0.4% in the 2017-2040 period up until 13.9% in the 2041-2070 period, for the RCP 4.5. Considering the RCP 8.5 scenario, the reduction could reach up to 25.3% in the 2071-2099 period, compared to the baseline period (2003-2016). Tan et al. (2017) assessing the climate change impacts under RCP scenarios on water resources of the Kelantan River Basin, Malaysia observed changes in precipitation of up to 8.7% and temperature increments of up to 2.1 °C during the 2045–2074 period under the RCP 8.5 scenario. Senent-Aparicio et al. (2017) assessing the impact of climate change in the headwaters of the Segura River Basin, Spain, found a negative trend in precipitation between 6% and 17% in the medium term (2041-2070) and 32% in the long term (2071-2100) under the RCP 8.5 scenario.

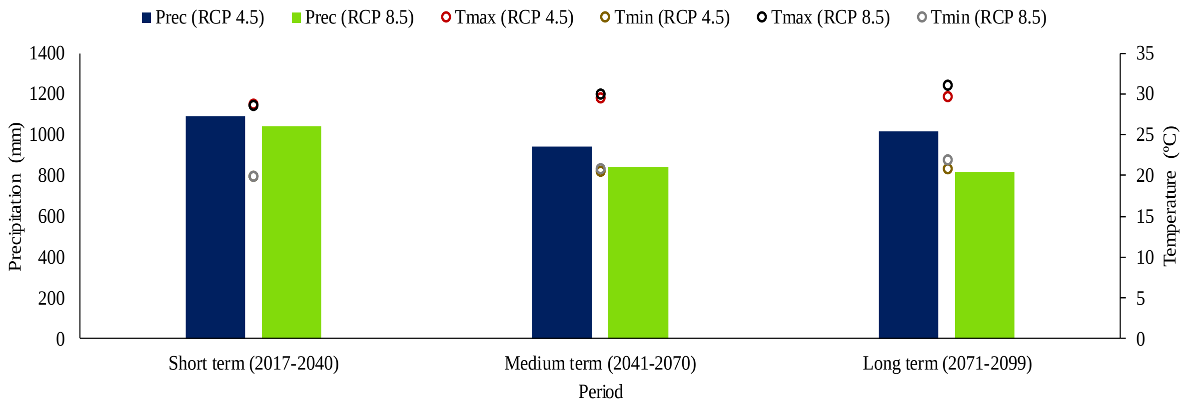


Fig. 5. Annual rainfall, maximum and minimum temperature changes at the MRB under two RCP scenarios for the 2017–2040, 2041-2070 and 2071–2099 periods

In seasonal terms, the RCPs project more precipitation in the rainy season (mainly in the months of June, July and August) in relation to the dry season, for all the periods under both RCPs. Much less precipitations are projected in the dry season, mainly in the months of November, December and January, for all periods under both RCPs. When comparing climate scenarios, RCP 8.5 has fewer months with rainfall greater than 40 mm and more months with less rainfall indices over the analyzed periods (short term, medium term and long term), when compared to RCP 4.5. These projected increases in temperature and changes in the intensity and pattern of precipitation are consistent with previous studies (Brouziyne et al., 2018; Carvalho-Santos et al., 2017; Oliveira et al., 2017; Ouyang et al., 2015; Senent-Aparicio et al., 2017). The increases in dry season temperatures could lead to water-scarcity. Moreover, high temperatures and low precipitation during these months might reduce agricultural productivity in the region (Narsimlu et al., 2013; Tan et al., 2017).

6.3.3 Hydrological processes under future climate change scenarios

The results of the changes in average annual hydrological processes for the MRB simulated by the SWAT model under climate scenarios and also for the baseline period are presented in Table 2 and Figure 6.

Simulated precipitation for the period 2071-2099 was 1014.2 and 815.6 mm under RCPs 4.5 and 8.5, respectively, decreasing by 7.2 and 25.3% in each scenario from the baseline. Simulated evapotranspiration (ET) under RCP 8.5 also decreased over time, since this process is closely related to precipitation, which also decreased. In the baseline period, simulated ET was 719.5 mm, while for the Eta-MIROC5 predictions the values decreased to a minimum of 652.8 mm under the long-term RCP 8.5. According to Tan et al. (2017) precipitation can significantly affect evapotranspiration. Potential evapotranspiration (ET_0) increased over time due to increasing temperatures, reaching a maximum value of 1641.1 mm under RCP 8.5 in the long term.

Table 2. Average annual hydrological processes for the MRB simulated by the SWAT model for the short term (2017-2040), medium term (2041-2070) and long term (2071-2099) under both RCP 4.5 and 8.5, and the baseline period for the basin

Process	Baseline (2003-2016)	Short term (2017-2040)		Medium term (2041-2070)		Long term (2071-2099)	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Precipitation (mm)	1092.52	1087.45	1041.07	939.69	839.38	1014.23	815.59
ET (mm)	719.50	780.77	765.58	720.04	676.18	759.19	652.83
ET_0 (mm)	1324.34	1509.55	1497.80	1560.24	1587.05	1548.47	1641.14
Surface runoff (mm)	181.99	43.57	39.82	34.46	21.35	42.51	24.48
Baseflow (mm)	156.44	205.23	190.03	156.84	117.92	182.26	113.57
Water yield (mm)	348.08	253.54	234.39	194.77	141.64	228.70	140.24

ET – evapotranspiration, ET_0 – potential evapotranspiration

Surface runoff in MRB is projected to decrease over time. In the baseline period runoff was approximately 182 mm and in the short, medium and long term scenarios this value fell to 43.6, 34.5 and 42.5 mm under RCP 4.5. In the more pessimistic scenario (RCP 8.5), these values decreased further, reaching 24.5 mm at the end of the 21st century. According to Nyssen et al. (2010) and Gebremicael et al. (2017), in semiarid watersheds, generally, there is a growing tendency in water abstractions, which can further reduce stream flows. Climate change is one of the factors that has a great influence in the surface runoff decrease (Abebe, 2014; Ashenafi, 2014; Tesfaye et al., 2017).

Shiferaw et al. (2018) found surface runoff decreases ranged from 1.75 to 0.74% in RCP 4.5 and from 0.76 to 0.36% in RCP 8.5. According to the authors, general increase in temperature will result in decreased surface runoff in the basin. As with the surface runoff, baseflow will also decrease over the analyzed periods. The results projected a minimum of 113.6 mm (decrease of 27.4%) for the period 2071-2099 under RCP 8.5. Narsimlu et al. (2013), assessing the future climate change impacts on water resources of Upper Sind River Basin, India, found a baseflow decrease of 8.9% when comparing the baseline period (1961-1990) with the midcentury (2021-2050).

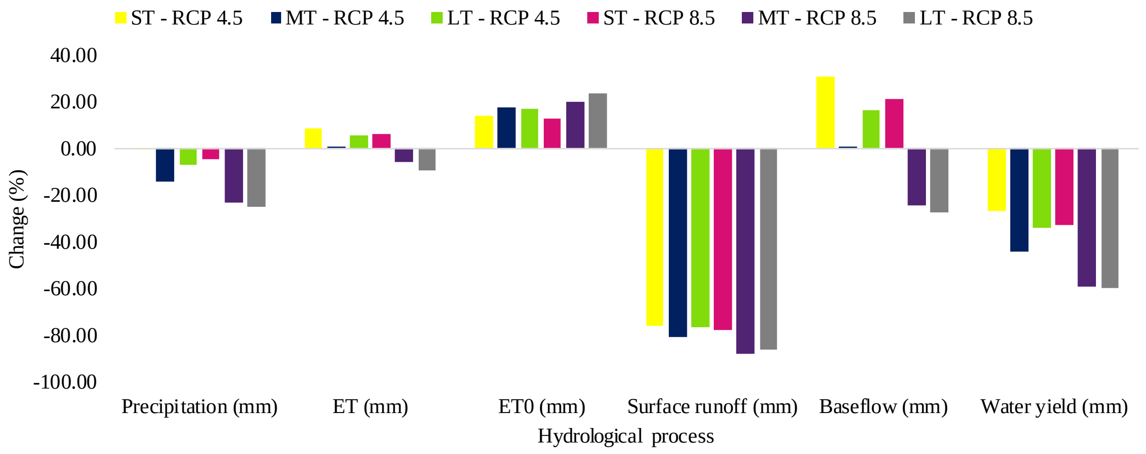


Fig. 6. Changes of annual climate and hydrological components for the periods of 2017–2040 (short term – ST), 2041-2070 (medium term – MT) and 2071–2099 (long term – LT) under RCPs. (ET – evapotranspiration, ET_0 – potential evapotranspiration)

The water yield is a hydrological process that can be representative of the water availability within a watershed (Sun et al., 2006). The results suggest that water yield within the MRB will decrease in the future, reaching 140.2 mm in RCP 8.5 in the long term. As a result, water resources may not be sufficient to support the demand of population and environment by the end of the 21st century. Therefore, effective and suitable water management planning should be conducted for the MRB in order to ensure water security in terms of quantity and quality, mainly during the dry season.

Decreases in precipitation and water yield are greater for RCP 8.5 than for RCP 4.5. This was to be expected, since according to Tan et al. (2017), the RCP 4.5 scenario indicates a medium forcing level (realistic emission) and the RCP 8.5 is a very high greenhouse gases emission scenario (pessimistic one).

6.3.4 Variations in streamflow under climate change

Projected annual streamflow changes for the 2017–2040, 2041–2070 and 2071-2099 periods under the two RCP scenarios are shown in Figure 7, and the percentage changes are presented in Figure 8. Although there were some differences between the scenarios and among the future periods, in general streamflow was predicted to decrease over the time, which could be attributed by rainfall decreases and temperature increases over the MRB. The reductions were more pronounced under the conditions of RCP 8.5 in the medium and long term, with drops of approximately 66.1 and 66.7%, respectively. In the short term (2017-2040), predicted streamflows under the RCP 4.5 and RCP 8.5 scenarios were closer to current streamflows than in the later time periods. Zhang et al. (2016) found relatively slight changes in streamflow in both RCP 2.6 and RCP 4.5, but increases under RCP 8.5 in the future. According to the authors, streamflow changes were generally associated with changes in rainfall. Ouyang et al. (2015) also found both increases and decreases in projected annual streamflow under RCPs 2.6, 4.5 and 8.5. According to the authors, the changes in annual streamflow were between -12.6 and 4.1 %, and -18 and 23.4% under RCPs 4.5 and 8.5, respectively.

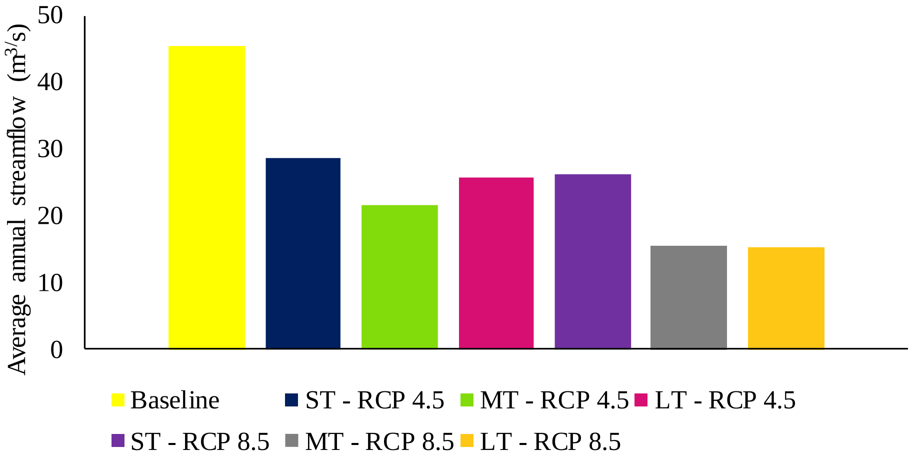


Fig. 7. Annual simulated streamflow by SWAT model for the future periods under RCPs scenarios compared with the baseline period

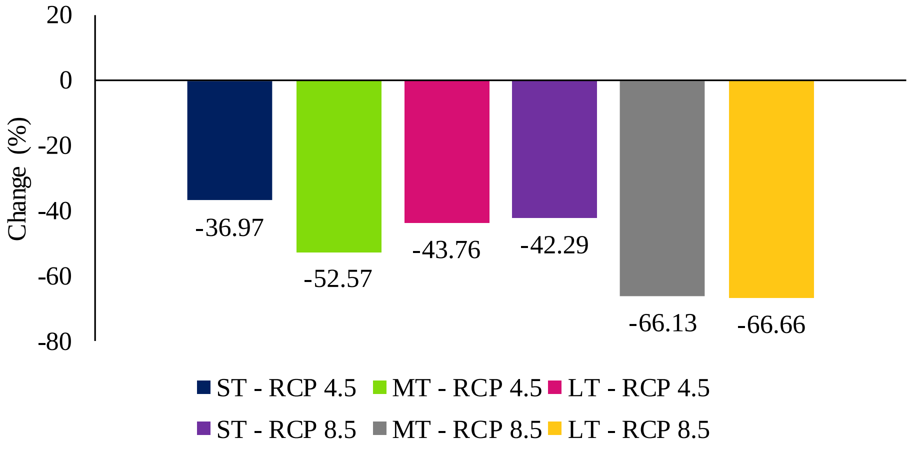


Fig. 8. Percentage change for the future periods under RCPs scenarios compared with the baseline period

Monthly simulated streamflows for the future periods under RCPs scenarios are presented in Figure 9. Comparing with the baseline streamflows, monthly streamflows tend to decrease over time. Mean monthly low flows are projected to decrease throughout the Mundaú River Basin, and the reductions were more pronounced for RCP 8.5 compared to RCP 4.5, reaching a minimum flow of 2.4 $m^3 s^{-1}$ in the month of December of the period

2071-2099. High flows are also projected to decrease over the MRB, with a maximum flow of 70.1 m³ s^{-1} in the month of July of the period 2017-2040 under the scenario RCP 4.5. In general, the streamflow patterns of the RCP 4.5 and 8.5 scenarios are very similar, but the magnitudes are different. The period of 2071–2099 is much drier for RCP8.5 compared to RCP 4.5. Yan et al. (2015) assessing the hydrological response to climate change under different RCP scenarios at the Pearl River, China, found similar results, with low, mean and highs flows projected to decrease throughout the Pearl River basin. According to the authors, constant low flows might rise. Ouyang et al. (2015) predicted streamflow decreases in all months in the future except September at Huangnizhuang catchment and attributed the decreases to increased temperatures and evapotranspiration. Oliveira et al. (2017) found with Eta-MIROC5 projections, a decreasing trend in average monthly and annual discharges by the end of the century under the RCPs 4.5 and 8.5, with reductions ranging from 1.9 to 37% compared with the baseline period. According to the authors, the low flows are associated with extreme and prolonged droughts, which may impact negatively water availability and other ecosystem services.

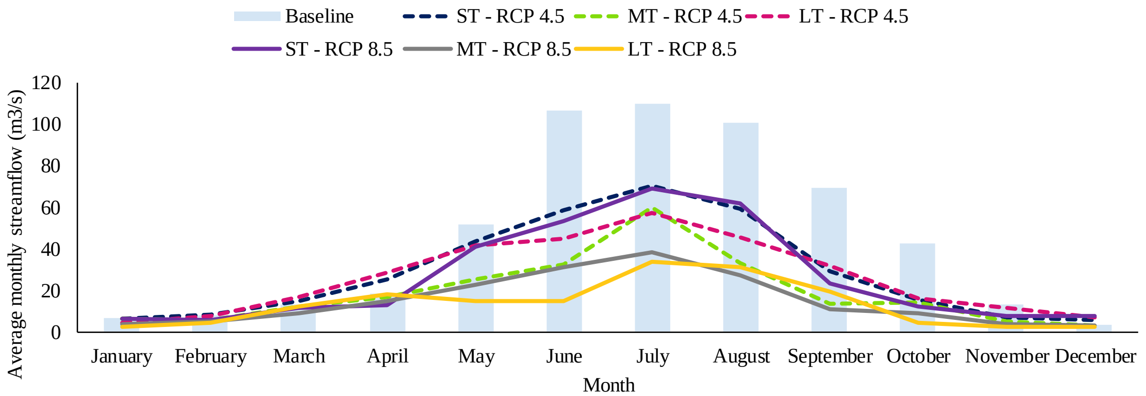


Fig. 9. Mean monthly simulated streamflows for the baseline and future periods under RCPs scenarios

Seasonal simulated streamflows for the future periods under RCPs scenarios are presented in Figure 10. Compared with the baseline, seasonal streamflows tended to decrease over the time, both in the rainy season (June, July and August) and in the dry season

(November, December and January). These reductions were more accentuated in the rainy season and in the long term, with a reduction of approximately 74.9% of the streamflow in the months of June, July and August under RCP 8.5 for the period 2071-2099. The decreases were more pronounced for RCP 8.5 than RCP 4.5, mainly in the medium and long term. Considering the short term, streamflow decreases were in the range of 40% for the two scenarios. For the dry period, the greatest reductions occurred with the RCP 8.5 scenario under the medium and long terms, with decreases of approximately 57 and 67%, respectively. The results found in this study indicate that the MRB will be drier and will experience less freshwater supply during both the wet and dry seasons due to climate changes. Senent-Aparicio et al. (2017) also found seasonal streamflow decreases for both periods (2041-2070 and 2071-2100) under RCPs 4.5 and 8.5 scenarios, with the largest reductions under the RCP 8.5 scenario in the period 2071-2100. Tan et al. (2017) found streamflow decreases in the wet season (July–September) and increases in the dry season (November–April). According to the authors, streamflows will decrease by 45–69% under RCP 4.5 in September and by 41–57% under RCP 8.5. However, streamflow will increase by 86–177% under RCP 4.5 in December and 82–156% under RCP 8.5.

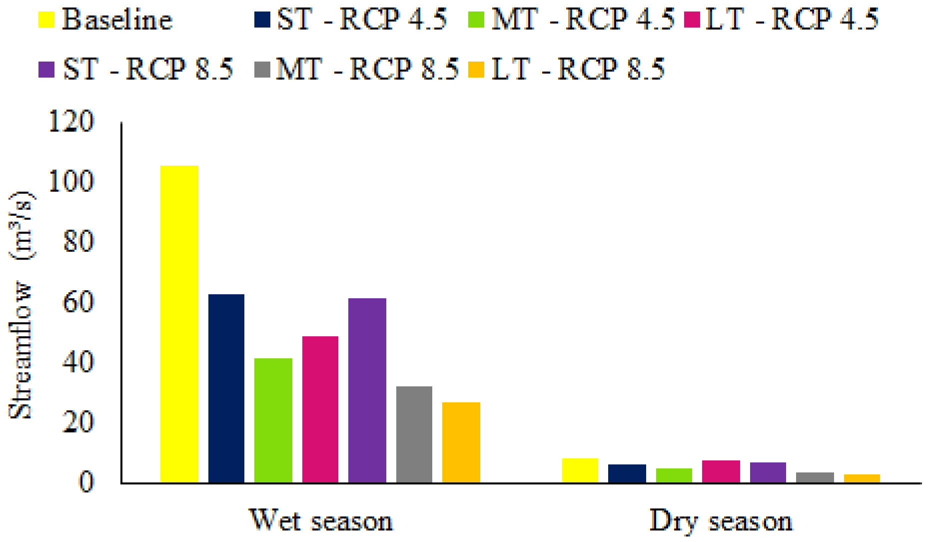


Fig. 10. Seasonal simulated streamflow by SWAT model for the future periods under RCPs scenarios compared with the baseline period

Yan et al. (2015) observed that in the Pearl River basin, the wet season will become wetter, and the dry season will become drier in the middle and lower reaches of the watershed. For upper area of the basin, both the dry and wet seasons will become drier. Streamflows increased in the wet seasons and decreased in the dry seasons. This condition leads to the increased flood frequencies and intensified drought stress, which might impact the economy and society. In contrast, Zhang et al. (2016) found reductions in streamflows during wet seasons and increases in dry seasons under future climate change scenarios. These results further reinforce the uncertainties associated with climate projections. It is challenging to project climate change accurately into the future, especially in terms of precipitation. The uncertainty can be attributed to: (1) uncertainty linked to several GCMs, (2) uncertainty associated to each representative concentration pathways (RCPs), (3) uncertainty to downscaling and bias correction methods and (4) uncertainty of hydrological models (Ouyang et al., 2015). Moreover, the uncertainties in future precipitation and temperature data can be propagated into streamflow simulation, and influence future water balance projections (Oliveira et al., 2017; Ouyang et al., 2015; Tan et al., 2017). That is why studies such as these are needed in order to better understand such projections and to make more realistic and reliable inferences about the future of the climate in the regions.

6.4 Conclusions

In the future, reductions in rainfall and increases in temperatures are expected in the MRB for the three time periods analyzed under the two RCP scenarios. In seasonal terms, less precipitation is expected in the rainy season and much less rainfall in the dry period. The projections of the Eta-MIROC5 indicated that the MRB will become warmer and drier, possibly causing water shortages throughout the basin.

This study predicts large effects of climate change on the water balance of the MRB. The processes expected to decrease over time were evapotranspiration, surface runoff, baseflow and water yield. On the other hand, potential evapotranspiration is expected to increase. Annual, monthly and seasonal streamflows are expected to decrease over the time, both in the rainy and dry seasons. These forecasts point to serious water availability problems and increased vulnerability of the region to water shortages in the future.

It is important to mention that uncertainties and systematic errors exist in all climate change impact research, including the GCMs, RCPs, bias correction methods and hydrological modeling. Nevertheless, studies like these are extremely important, since they seek to reduce these uncertainties and provide information to mitigate the impacts of climate change on the future hydrological behavior of the basins.

Finally, the water balance of the Mundaú River Basin may, in the future, be strongly influenced by climate change, affecting the water availability and streamflow patterns. To mitigate climate change impacts, evaluation of appropriate adaptation strategies is essential. The results of this study can be used by water resource managers in decision making on the appropriate uses of water, in the creation of public policies that favor appropriate uses, and in the adoption of mitigation and prevention practices to ensure water security in this and other agro-ecologically similar watersheds.

References

Abbaspour, K.C., Yang, J., Maximov, I., Siber, R., Bogner, K., Mieleitner, J. Zobrist, J., Srinivasan, R., 2007. Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. Journal of Hydrology, 333, 413-430. http://doi.org/10.1016/j.jhydrol.2006.09.014.

Abebe, B.A., 2014. Modeling the effect of climate and land use change on the water resources in Northern Ethiopia: the case of Suluh River Basin. (Ph.D. Thesis in Physical Geography) – Freie University of Berlin, 168p.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M., Sparovek, G., 2014. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift, 22, 6, 711–728. https://doi.org/10.1127/0941-2948/2013/0507.

APAC, Agência Pernambucana de Águas e Clima (Pernambuco State Agency for Water and Climate) (www.apac.pe.gov.br). Accessed on: July 2015.

Arnell, N.W., 1999. Climate change and global water resources. Glob. Environ. Chang., 9, 31–49. https://doi.org/10.1016/S0959-3780(99)00017-5.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment part I: model development. Journal of the American Water Resources Association, 34, 73-89. http://dx.doi.org/10.1111/j.1752-1688.1998.

Ashenafi, A.A., 2014. Modeling hydrological responses to changes in land cover and climate in Geba River Basin, Northern Ethiopia. (Ph.D. Thesis in Physical Geography) – Freie University of Berlin, 187p.

Block, P.J., Souza Filho, F.A., Sun, L., Kwon, H.H., 2009. A streamflow forecasting framework using multiple climate and hydrological models 1. J. Am. Water Resour. As., 45, 4, 828–843. http://dx.doi.org/10.1111/j.1752-1688.2009.00327.x.

Brouziyne, Y., Abouabdillah, A., Hirich, A., Bouabid, R., Zaaboul, R., Benaabidate, L., 2018. Modeling sustainable adaptation strategies toward a climate-smart agriculture in a Mediterranean watershed under projected climate change scenarios. Agricultural Systems, 162, 154-163. https://doi.org/10.1016/j.agsy.2018.01.024.

Carvalho-Santos, C., Monteiro, A.T., Azevedo, J.C., Honrado, J.P., Nunes, J.P., 2017. Climate change impacts on water resources and reservoir management: uncertainty and adaptation for a mountain catchment in northeast Portugal. Water Resour Manage, 31, 3355–3370. https://doi.org/10.1007/s11269-017-1672-z.

Chen, J., Brissette, F., Lucas-Picher, P., 2016. Transferability of optimally-selected climate models in the quantification of climate change impacts on hydrology. Clim. Dyn., 47, 3359–3372. https://doi.org/10.1007/s00382-016-3030-x.

Chou, S.C., Lyra, A., Mourão, C., Dereczynski, C., Pilotto, I., Gomes, J., Bustamante, J., Tavares, P., Silva, A., Rodrigues, D., Campos, D., Chagas, D., Sueiro, G., Siqueira, G., Marengo, J., 2014a. Assessment of climate change over South America under RCP 4.5 and 8.5 downscaling scenarios. Am. J. Clim. Change, 3, 5, 512–525. https://doi.org/10.4236/ajcc.2014.35043.

Chou, S.C, Lyra, A., Mourão, C., Dereczynski, C., Pilotto, I., Gomes, J., Bustamante, J., Tavares, P., Silva, A., Rodrigues, D., Campos, D., Chagas, D., Sueiro, G., Siqueira, G., Nobre, P., Marengo, J.A., 2014b. Evaluation of the Eta simulations nested in three global climate models. Am. J. Clim. Change 3, 5, 438–454. https://doi.org/10.4236/ajcc.2014.35039.

Cuo, L., Zhang, Y., Zhu, F., Liang, L., 2015. Characteristics and changes of streamflow on the Tibetan Plateau: a review. Journal of Hydrology: Regional Studies, 2, 49–68. https://doi.org/10.1016/j.ejrh.2014.08.004.

Deb, D., Butcher, J., Srinivasan, R., 2014. Projected hydrologic changes under mid-21st century climatic conditions in a sub-arctic watershed. Water Resour. Manage. 29, 5, 1467–1487. https://doi.org/10.1007/s11269-014-0887-5.

Estrela, T., Pérez-Martín, M.A., Vargas, E., 2012. Impacts of climate change on water resources in Spain. Hydrol. Sci. J., 57, 1154–1167. https://doi.org/10.1080/02626667.2012.702213.

Gebremicael, T.G., Mohamed, Y.A., Zaag, P.V., Hagos, E.Y., 2017. Temporal and spatial changes of rainfall and streamflow in the Upper Tekezē-Atbara river basin, Ethiopia. Hydrol Earth Syst Sci, 21, 2127–2142. https ://doi.org/10.5194/hess-21-2127-2017

Gonzalez, P., Neilson, R.P., Lenihan, J.M., Drapek, R.J., 2010. Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. Glob. Ecol. Biogeogr. 19, 6, 755–768. https://doi.org/10.1111/j.1466-8238.2010.00558.x.

Graham, L.P., Andréasson, J., Carlsson, B., 2007. Assessing climate change impacts on hydrology from an ensemble of regional climate models, model scales and linking methods – a case study on the Lule River basin. Clim. Change, 81, 293–307. https://doi.org/10.1007/s10584-006-9215-2.

Haddeland, I., Heinke, J., Vob, F., Eisner, S., Chen, C., Hagemann, S., Ludwig, F., 2012. Effects of climate model radiation, humidity and wind estimates on hydrological simulations. Hydrol. Earth Syst. Sci. 16, 2, 305–318. https://doi.org/10.5194/hess-16-305-2012.

Intergovernmental Panel on Climate Change. 2013. Climate change 2013: the physical science basis. Synthesis Report, Cambridge University Press, Cambridge, UK. http://www.ipcc.ch/report/ar5/wg1/ (accessed on April 2018).

Jing, Z., Dan, H., Xie, Y., Yong, L., Yang, Y., Hu, S., Guo, H., Lei, Z., Rui, Z., 2015. Integrated SWAT model and statistical downscaling for estimating streamflow response to climate change in the Lake Dianchi watershed, China. Stoch. Env. Res. Risk A, 29, 4, 1193–1210. https://doi.org/10.1007/s00477-015-1037-1.

Leal, I.R., Silva, J.M.C., Tabarelli, M., Lacher Junior, T.E., 2005. Changing the course of biodiversity conservation in the Caatinga of Northeastern Brazil. Conservation Biology, 19, 701-706. http://dx.doi.org/10.1111/j.1523-1739.2005.00703.x.

Lenderink, G., Buishand, A., Van Deursen, W., 2007. Estimates of future discharges of the river Rhine using two scenario methodologies: direct versus delta approach. Hydrol. Earth Syst. Sci., 11, 3, 1145–1159. https://doi.org/10.5194/hess-11-1145-2007.

Meinshausen, M., Smith, S.J., Calvin, K., Calvin, K., Daniel, J.S., Kainuma, M.L.T., Lamarque, J-F., Matsumoto, K., Montzka, S.A., Raper, S.C.B., Riahi, K., Thomson, A., Velders, G.J.M., van Vuuren, D.P.P., 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Clim Chang, 109, 213–241. https://doi.org/10.1007/s10584-011-0156-z.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A, Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. Nature, 463, 747–756. https://doi.org/10.1038/nature08823.

Narsimlu, B., Gosain, A.K., Chahar, B.R., 2013. Assessment of future climate change impacts on water resources of Upper Sind River Basin, India using SWAT model. Water Resour Manage, 27, 3647–3662, https://10.1007/s11269-013-0371-7.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2005. Soil and water assessment tool: Theoretical documentation version 2005. Temple: Blackland Research Center, 541p.

Nyssen, J., Clymans, W., Descheemaeker, K., Poesen, J., Vandecasteele, I., Vanmaercke, M., Zenebe, A., van Camp, M., Haile, M., Haregeweyn, N., Moeyersons, J., Martens, K., Gebreyohannes, T., Deckers, J., Walraevens, K., 2010. Impact of soil and water conservation measures on catchment hydrological response – a case in north Ethiopia. Hydrol Process, 24, 1880–1895. https ://doi.org/10.1002/hyp.7628.

Oliveira, V.A., Mello, C.R., Viola, M.R., 2017. Srinivasan, R. Assessment of climate change impacts on streamflow and hydropower potential in the headwater region of the Grande river basin, Southeastern Brazil. Int. J. Climatol., 37, 5005–5023. https://doi.org/10.1002/joc.5138.

Ouyang, F., Zhu, Y., Fu, G., Lu, H., Zhang, A., Yu, Z., Chen, X., 2015. Impacts of climate change under CMIP5 RCP scenarios on streamflow in the Huangnizhuang catchment. Stoch Environ Res Risk Assess, 29, 1781–1795. https://doi.org/10.1007/s00477-014-1018-9.

Paparrizos, S., Maris, F., Matzarakis, A., 2016. Integrated analysis of present and future responses of precipitation over selected Greek areas with different climate conditions. Atmos. Res., 169, Part A, 199–208. https://doi.org/10.1016/j.atmosres.2015.10.004.

Pervez, M.S., Henebry, G.M., 2015. Assessing the impacts of climate and land use and land cover change on the freshwater availability in the Brahmaputra River basin. Journal of Hydrology: Regional Studies, 3, 285–311. https://doi.org/10.1016/j.ejrh.2014.09.003.

Piani, C., Haerter, J.O., Coppola, E., 2010. Statistical bias correction for daily precipitation in regional climate models over Europe. Theor. Appl. Climatol., 99, 1, 187–192. http://dx.doi.org/10.1007/s00704-009-0134-9.

Piani, C., Weedon, G.P., Best, M., Gomes, S.M., Viterbo, P., Hagemann, S., Haerter, J.O.,

2009. Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models. Journal of Hydrology, 395, 199–215. http://dx.doi.org/10.1016/j.jhydrol.2010.10.024.

Rajib, M., Rahman, M., 2012. A comprehensive modeling study on regional climate model (RCM) application - regional warming projections in monthly resolutions under IPCC A1B scenario. Atmosphere 3, 4, 557–572. https://doi.org/10.3390/atmos3040557.

Rathjens, H., Bieger, K., Srinivasan, R., Chaubey, I., Arnold, J.G., 2016. CMhyd User Manual. Available online: http://swat.tamu.edu/software/cmhyd/ (accessed on March 2018).

Senent-Aparicio, J., Pérez-Sánchez, J., Carrillo-García, J., Soto, J., 2017. Using SWAT and Fuzzy TOPSIS to assess the impact of climate change in the headwaters of the Segura River Basin (SE Spain). Water, 9, 149. http://dx.doi.org/10.3390/w9020149.

Shiferaw, H., Gebremedhin, A., Gebretsadkan, T., Zenebe, A., 2018. Modelling hydrological response under climate change scenarios using SWAT model: the case of Ilala watershed, Northern Ethiopia. Modeling Earth Systems and Environment, 4, 437–449. https://doi.org/10.1007/s40808-018-0439-8.

Silva, C.A.I., 2014. Análise de aplicabilidade da interface do modelo hidrológico SWAT-SIG no estudo da produção de sedimentos em uma bacia no Nordeste do Brasil. Dissertation (Master in Water Resources and Sanitation) - Federal University of Alagoas, 53p.

Sousa, R.M., 2017. Mudanças climáticas futuras simuladas pelos modelos regionais Eta-HADGEM2-ES e Eta-MIROC5 para o estado do Tocantins. Dissertation (Master in Forestry and Environmental Sciences) - Federal University of Tocantins, 96p.

Sun, G., Zhou, G.Y., Zhang, Z.Q., Wei, X.H., McNulty, S.G., Vose, J.M., 2006. Potential water yield reduction due to forestation across China. J. Hydrol., 328, 3–4, 548–558. https://doi.org/10.1016/j.jhydrol.2005.12.013.

Tan, M.L., Ibrahim, A.L., Yusop, Z., Chua, V.P., Chan, N.W., 2017. Atmospheric Research, 189, 1–10. http://dx.doi.org/10.1016/j.atmosres.2017.01.008.

Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An overview of CMIP5 and the experiment design. Bull. Am. Meteorol. Soc., 93, 4, 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1.

Tesfaye, S., Birhane, E., Leijnse, T., Zee, S.E.A.T.M. van der, 2017. Science of the total environment climatic controls of ecohydrological responses in the highlands of northern Ethiopia. Sci Total Environ, 609, 77–91. https ://doi.org/10.1016/j.scito tenv.2017.07.138.

Teutschbein, C., Seibert, J., 2012. Bias corretion of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. J. Hydrol., 456–457, 12–29. https://doi.org/10.1016/j.jhydrol.2012.05.052.

Urrutia, R., Vuille, M., 2009. Climate change projections for the tropical Andes using a regional climate model: temperature and precipitation simulations for the end of the 21st century. J. Geophys. Res.-Atmos., 114, 1–15. https://doi.org/10.1029/2008JD011021.

Vaghefi, S.A., Abbaspour, N., Kamali, B., Abbaspour, K.C., 2017. A toolkit for climate change analysis and pattern recognition for extreme weather conditions e Case study: California-Baja California Peninsula. Environmental Modelling & Software, 96, 181-198. http://dx.doi.org/10.1016/j.envsoft.2017.06.033.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview, 109, 5-31. http://dx.doi.org/10.1007/s10584-011-0148-z.

Watanabe, M., Suziki, T., O'ishi, R., Komuro, Y., Watanabe, S., Emori, S., Takemura, T., Chikira, M., Ogura, T., Sekiguchi, M., Takata, K., Yamazaki, D., Yokohata, T., Nozawa, T., Hasumi, H., Tatebe, H., Kimoto, M., 2010. Improved climate simulation by MIROC5: mean states, variability, and climate sensitivity. J. Clim., 23, 23, 6312–6335. https://doi.org/10.1175/2010JCLI3679.1.

Werneck, F.P., 2011. The diversification of eastern South American open vegetation biomes: Historical biogeography and perspectives. Quaternary Science Reviews, 30, 1630-1648. https://dx.doi.org/10.1016/j.quascirev.2011.03.009.

Wilby, R.L., Dawsonb, C.W., Barrowc, E.M., 2002. SDSM — a decision support tool for the assessment of regional climate change impacts. Environ. Model. Softw. 17, 2, 147–159. https://doi.org/10.1016/S1364-8152(01)00060-3.

Yan, D., Werners, S.E., Ludwig, F., Huang, H.Q., 2015. Hydrological response to climate change: The Pearl River, China under different RCP scenarios. Journal of Hydrology: Regional Studies, 4, 228–245. http://dx.doi.org/10.1016/j.ejrh.2015.06.006.

Zhang, Q.A., Xu, C.Y., Zhang, Z.X., Chen, Y.D., 2010. Changes of atmospheric water vapor budget in the Pearl River Basin and possible implications for hydrological cycle. Theor. Appl. Climatol. 102, 1–2, 185–195. https://doi.org/10.1007/s00704-010-0257-z.

Zhang, Y., You, Q., Chen, C., Ge, J., 2016. Impacts of climate change on streamflows under RCP scenarios: A case study in Xin River Basin, China. Atmospheric Research, 178–179, 521–534. http://dx.doi.org/10.1016/j.atmosres.2016.04.018.

7. General Conclusions and Recommendations

In this study, we analyze the uncertainties associated with the calibration and validation of the SWAT model for the Mundaú River Basin and simulate scenarios of land use and climate changes. More specifically, we evaluated the effects of the use of two variables (discharge and soil moisture) and five streamflow gauge stations along the watershed on calibration and validation of the SWAT, assessed the effect of land use changes on evapotranspiration, surface runoff and sediment yield of the study watershed, and verified the impacts on water resources of the future climate change from the Regional Climate Model (RCM) Eta-MIROC5.

Considering the representativeness of the watershed and the data scarcity for hydrological modeling in the MRB, we believe the results are very satisfactory and offer important understanding into the water availability and extreme events in the basin. The calibration of the SWAT model in the MRB presented "satisfactory" and "very good" performances, according to the statistical indices obtained for both the calibration and validation phases. Additionally, although there is a considerable amount of uncertainty, the use of a series of alternative data to calibrate and validate the SWAT model, such as soil moisture data, is a feasible and promising option for hydrological modeling, especially when hydrological and meteorological data series has low availability, as is the case in some of the Brazilian semiarid watersheds.

This study confirmed that the Mundaú River Basin experienced significant land use changes between 1987 and 2017. We found that over the 30 years (1987-2017) there was an increase in processes such as surface runoff and sediment yield. On the other hand, there was a reduction in the evapotranspiration. Hence, it can be concluded that spatial and temporal distribution of land use controls the water balance and sediment production in the Mundaú River Basin.

According to the climate change scenarios, in the future, a general rainfall reduction and temperatures increase is expected in the Mundaú River Basin for all time periods under the two RCP scenarios. This conditions may cause problems such as water shortage throughout the basin. Additionally, there will be a considerable effect of climate change on water balance of the basin. The processes that obtained a tendency to reduce over time and the scenarios were evapotranspiration, surface runoff, baseflow and water yield. On the other hand, potential evapotranspiration showed a tendency of growth. Also, the seasonal streamflow tends to decrease over the time, both in the rainy and dry season. This condition causes a negative impact on the runoff generation of the watershed and consequently increases the vulnerability of the region regarding water uses in the future. In general, the water balance of the Mundaú River Basin may, in the future, be very influenced due to the projected climate change, affecting the water availability and streamflow patterns. To deal with the issues of the climate change impacts, evaluation of appropriate adaptation strategies is essential.

Finally, the outcomes achieved were very encouraging. SWAT allows the hydrological processes on the Mundaú to be suitably represented. The findings of this study can assist water resource managers in decision making on the appropriate use of water, in the creation of public policies that favor the appropriate use, in the adoption of mitigation and prevention practices, in order to ensure the water security in the watershed and in other agro-ecologically similar watersheds.

As recommendations, we believe that the hydrological simulation with the SWAT model in the Mundaú River Basin can be improved with the insertion of a new land use class in the model database, representing the Caatinga biome, since it is exclusive of the Brazilian semiarid. In addition, the input data for the land use map should be improved in terms of resolution and insertion of new classes, in order to better detail the land use characteristics in the basin, and to improve the model predictions. New calibrations can be performed in the study area, using other alternative data, such as evapotranspiration data, leaf area index, water table level, among others. All these modifications highlight the importance of hydro-climatological monitoring and parameters related to soil and crops determination, which must be performed constantly in the region.

8. Publications and other relevant activities conducted on the doctoral research

8.1 Papers accepted in peer-review international journals

1. Andrade, C.W.L., Montenegro, S.M.G.L., Montenegro A.A.A., Lima, J.R.S., Srinivasan, R. and Jones, C.A., 2018. Soil moisture and discharge modeling in a representative watershed in northeastern Brazil using SWAT. Ecohydrology & Hydrobiology.

8.2 Papers submitted in peer-review international journals

1. Andrade, C.W.L., Montenegro, S.M.G.L., Montenegro A.A.A., Lima, J.R.S., Srinivasan, R. and Jones, C.A., 2018. Assessment of climate change impacts on water resources under RCP scenarios: A case study in the Mundaú River Basin, northeastern Brazil. International Journal of Climatology.

8.3 Papers published in peer-review journals

1. Andrade, C.W.L., Montenegro, S.M.G.L., Lima, J.R.S., Montenegro, A.A.A., Srinivasan, R., 2017. Análise de sensibilidade de parâmetros do modelo SWAT em uma sub-bacia da região Nordeste, Brasil. Revista Brasileira de Geografia Física, 10, 440-453.

2. Andrade, C.W.L., Montenegro, S.M.G.L., Lima, J.R.S., Montenegro, A.A.A., Magalhães, A.G., 2017. Modelagem hidrológica sob escassez de dados na Bacia do Alto Mundaú, Nordeste do Brasil. Journal of Environmental Analysis and Progress, 2, 227-238.

3. Andrade, C.W.L., Montenegro, S.M.G.L., Lima, J.R.S., Montenegro, A.A.A., Magalhães, A.G., 2017. Modelagem hidrológica sob mudanças na cobertura vegetal

de uma bacia hidrográfica no Nordeste do Brasil. Journal of Environmental Analysis and Progress, 2, 239-248.

8.4 Papers or abstracts submitted in conference proceedings

1. Andrade, C.W.L., Montenegro, S.M.G.L., Montenegro, A.A.A., Lima, J.R.S. 2018. Análise de consistência de dados de precipitação na bacia hidrográfica do rio mundaú, Nordeste do Brasil. In: XIV Simpósio de Recursos Hídricos do Nordeste, Maceió - AL.

2. Andrade, C.W.L., Montenegro, S.M.G.L., Montenegro, A.A.A., Lima, J.R.S. 2018. Análise de coberturas do solo existentes no banco de dados do modelo SWAT para associação com a vegetação Caatinga do Nordeste brasileiro. In: XIV Simpósio de Recursos Hídricos do Nordeste, Maceió - AL.

8.5 Papers or abstracts published and/or presented in conference proceedings

1. Carvalho, W.A., Andrade, C.W.L., 2018. Modelagem hidrológica na bacia hidrográfica do Alto Mundaú utilizando a interface SIG-SWAT (QSWAT). In: II Simpósio de Aquicultura e Recursos Pesqueiros, Serra Talhada – PE.

2. Andrade, C.W.L., Montenegro, S.M.G.L., Lima, J.R.S., Montenegro, A.A.A., Magalhães, A.G., 2017. Modelagem hidrológica sob mudanças na cobertura vegetal de uma bacia hidrográfica no Nordeste do Brasil. In: XX Congresso Brasileiro de Agrometeorologia, Juazeiro – BA.

3. Andrade, C.W.L., Montenegro, S.M.G.L., Lima, J.R.S., Montenegro, A.A.A., Magalhães, A.G., 2017. Modelagem hidrológica sob escassez de dados na Bacia do Alto Mundaú, Nordeste do Brasil. In: XX Congresso Brasileiro de Agrometeorologia, Juazeiro – BA.

4. Andrade, C.W.L., Montenegro, S.M.G.L., Lima, J.R.S., Magalhães, A.G., Srinivasan, R., 2016. Modelagem hidrológica de uma sub-bacia do Alto Mundaú utilizando o modelo SWAT. In: XIII Simpósio de Recursos Hídricos do Nordeste, Aracajú - SE.
5. Andrade, C.W.L., Montenegro, S.M.G.L., Lima, J.R.S., Montenegro, A.A.A., 2016. Estimativa do balanço hídrico de uma sub-bacia do Nordeste brasileiro com o modelo SWAT. In: XVI Jornada de Ensino, Pesquisa e Extensão da UFRPE, Recife – PE.
6. Andrade, C.W.L., Montenegro, S.M.G.L., Lima, J.R.S., Montenegro, A.A.A., 2016. Análise de sensibilidade de parâmetros do modelo SWAT em uma sub-bacia do Nordeste brasileiro. In: XVI Jornada de Ensino, Pesquisa e Extensão da UFRPE, Recife – PE.
7. Andrade, C.W.L., Montenegro, S.M.G.L., Ribeiro Neto, A. 2015. Estimation of input parameters of SWAT model through geoprocessing. In: 2015 Sardinia SWAT Conference, Pula, Sardinia, Italy.

8.6 Participation in conferences

1. VIII Workshop de Mudanças Climáticas e Recursos Hídricos do Estado de Pernambuco e V Workshop Internacional de Mudanças Climáticas e Biodiversidade. 2017. Recife – PE.
2. XX Congresso Brasileiro de Agrometeorologia. 2017. Juazeiro – BA.
3. XIII Simpósio de Recursos Hídricos do Nordeste. 2016. Aracajú – SE.
4. XVI Jornada de Ensino, Pesquisa e Extensão da UFRPE. 2016. Recife – PE.
5. 2015 Sardinia SWAT Conference. 2015. Pula, Sardinia, Italy.
6. Workshop Introdutório do Modelo SWAT. 2015. Recife – PE.
7. Workshop Introdutório do Modelo SWAT. 2014. Recife – PE.

8.7 Courses

1. Curso introdutório do modelo SWAT. (Carga horária: 40 h). Universidade Federal de Pernambuco, UFPE, 2015.
2. Curso introdutório do modelo SWAT. (Carga horária: 16 h). Universidade Federal de Pernambuco, UFPE, 2014.
3. Advanced plant- based, internet- sensor technology increases water efficiency in agriculture: a proactive response to water shortages and climate changes. Universidade Federal Rural de Pernambuco, UFRPE, 2014.

8.8 Sandwich Doctorate at Texas A&M University

The Sandwich Doctorate was developed from 10/10/2015 until 02/16/2016 at Texas A&M University, located in the city of College Station, Texas, USA, under the supervision of Dr. Raghavan Srinivasan. The subsidy for the development of the research project was contemplated by the project PVE 024/2015 (Proc. 23038007733 / 2013-76) “Uso do SWAT para modelagem hidrológica da bacia hidrográfica do São Francisco e de bacias experimentais e representativas” of the Ciência sem Fronteiras program, funded by CAPES.

Part of the Doctoral research was developed during the Sandwich Doctorate. The activities performed were: 1. Information collect on land use, soil and climate of the Mundaú River Basin. 2. Literature review, with recently published papers. 3. Perform of the first simulations (tests) with the SWAT model.

The analysis during the Sandwich Doctorate were performed in two sub basins belonging to the total area of the study, the Mundaú River Basin. During the months of October, November and December of 2015, the information and data collect required for the hydrological simulation with the SWAT model was performed. In addition, literature reviews and SWAT manuals were conducted. All sources of information and input data required for hydrological simulation were described previously in Chapter 2. In the following months, the hydrologic simulation was performed from the latest SWAT version, ArcSWAT 2012, which was coupled to the ArcGis™ software version 10.1. The outputs of the model were analyzed and the results obtained in the Sandwich Doctorate represented the first of a series of simulations carried out during the Doctorate course, with the improvement of the simulations, the development of the calibration, validation, sensitivity and uncertainty analyzes, in addition to simulations of land use and climate change scenarios.

The period of study carried out in the Sandwich Doctorate was extremely important for this Doctoral research, since important decisions related to hydrological modeling, such as definition of the data period, management adopted, choice of sources of input data, and the own modeling with the SWAT, were started in that period. For this reason, the sincere thanks are reaffirmed here, to Professor Raghavan Srinivasan, as well as to all researchers at Texas A&M University, for their generous technical support.

Attachments

Table 1. Information obtained from literature, related to soil texture and organic matter of the Mundaú River Basin and nearby regions, for the application of pedotransfer functions proposed by Saxton and Rawls (2006)

Nº.	**Soil name**	**Municipality/ State**	**Horizon**	**Layer (cm)**	**Sand (%)**			**Silt (%)**	**Clay (%)**	**Organic Carbon (%)**
					Coarse	**Thin**	**Total**			
1	Red-Yellow Oxisol	Maceió/ AL	A1	0-7	41	25	66	5	29	0.98
			A3	7-25	43	17	60	4	36	0.08
			B1	25-55	27	27	54	5	41	0.67
			B21	55-120	27	17	42	3	55	0.3
			B22	120-170	25	12	37	4	59	0.22
			B3	170-220+	22	13	35	5	60	0.21
2	Red-Yellow Argisol	São Jose da Laje/ AL	A1	0-35	22	33	55	18	27	1.76
			B1	35-65	8	17	25	9	66	0.63
			B2	65-120	2	24	26	16	58	0.44
			B3	120-145	11	29	40	22	38	0.3
			C1	145-170	32	21	53	18	29	0.19
3	Mangrove soil	Penedo/ AL	Ap	0-10	0	24	24	25	51	4.24
			IIC1g	10-20	1	5	6	34	60	1.6
			IIIC2g	20-45	1	10	11	20	69	0.9
			IVC3g	45-70	2	11	13	38	49	0.55
			VC4g	70-90	4	13	17	40	43	0.4
			VIC5g	90-130+	1	25	26	35	39	0.5
4	Gleisol	Coruripe/ AL	Ap	0-20	5	7	12	33	55	2.12
			Cg	20-75	1	2	3	30	67	0.86
			Cgvzn1	75-120	1	1	2	27	71	0.49
			Cgvzn2	120-180	0	1	1	22	77	0.6
5	Yellow Oxisol	Coruripe/ AL	Ap	0-25	74	0	74	5	21	0.95
			BA	25-50	62	0	62	13	25	0.46

			Bw1	50-115	55	0	55	9	36	0.28
			Bw2	115-200	37	0	37	15	48	0.21
6	Yellow Argisol	Coruripe/ AL	Ap	0-20	83	0	83	5	12	1.41
			AB	20-55	75	0	75	5	20	0.53
			BA	55-85	49	0	49	9	42	0.37
			Btx	85-135	30	0	30	14	56	0.23
			Bt	135-210+	23	0	23	17	60	0.21
7	Quartzarenic Neosol	Coruripe/ AL	Ap	0-25	69	25	94	4	2	0.4
			C1	25-55	68	28	96	2	2	0.08
			C2	55-100	61	31	92	6	2	0.05
			C3	100-150+	63	30	93	5	2	0.05
8	Planosol	União dos Palmares/ PE	Ap1	0-30	33	39	72	19	9	0.67
			IIBt	50-70	53	8	61	7	32	0.25
			IIC	70-90	44	17	61	11	28	0.17
9	Litolic soil	Taquarana/ AL	A	0-35	56	27	83	12	5	0.47
10	Fluvic Neosol	Colônia Leopoldina/ AL	Ap	0-22	41	37	78	13	9	0.44
			C1	22-42	43	36	79	12	9	0.17
			IIC2	42-100+	45	35	80	11	9	0.13
11	Yellow Oxisol	Brejão/ PE	A1	0-15	61	8.3	69.3	2.6	28.1	3.11
			A2	15-35	61.8	7.2	69	1.8	29.2	2.84
			A3	35-67	50.7	12.8	63.5	3.3	33.2	1.89
			AB	67-100	38	8.2	46.2	3	50.8	1.41
			BA	100-135	41.3	8.9	50.2	1.8	48	1.01
			Bw	135-190+	36.8	10.2	47	3.2	49.8	0.64
12	Planosol	São Caetano/ PE	Ap	0-12	31	34	65	24	11	0.64
			Bt	12-26	31	24	55	21	24	0.35
			Btn	26-40	25	21	46	18	36	0.3
			Cn	40-53	30	24	54	24	22	0.23
			Crn	53-100+	50	31	81	11	8	0.05
13	Neosol	São Caetano/ PE	Surface	0-20	79	5	84	7	9	1.32
			Subsurface	20-58	59	21	80	9	11	0.7
14	Red-Yellow Argisol	Jupi/ PE	Surface	0-12	71	15	86	6	8	1.24

			Subsurface	12-75	61	19	80	6	14	0.7
15	Yellow Argisol	Garanhuns/ PE	Surface	0-15	55	11	66	6	28	3.5
			Subsurface	15-37	49	10	59	5	36	2.25
16	Litolic soil	Caruaru/ PE	Surface	0-6	43.2	22	65.2	21.4	13.4	4
			Subsurface	6-16	48.4	20.4	68.8	17.6	13.6	4