# Review of Soil and Water Assessment Tool (SWAT) applications in Brazil: Challenges and prospects

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

**Keywords:** SWAT, models, mapping applications, review, Brazil

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## 1 Introduction

The Brazilian National Water Resources Policy (NWRP)[1,2] was approved in 1997, with the intent of meeting the objectives and principles of Integrated Water

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

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

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

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

## 2 Brazilian biomes and environmental conditions

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

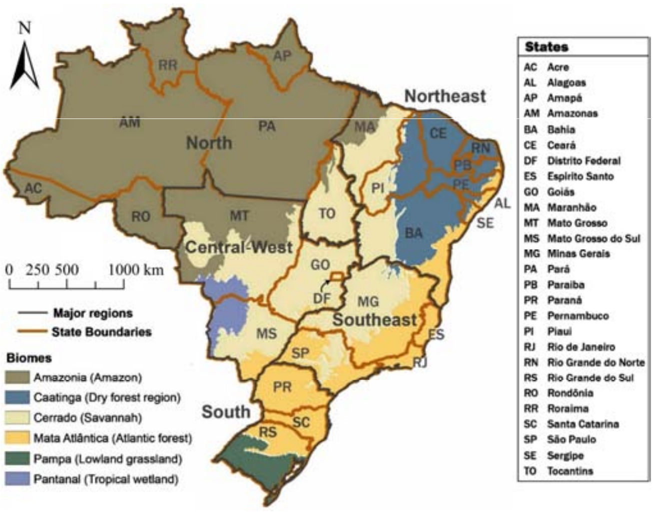


Figure 1 Location of major geographical regions, states and biomes[29] in Brazil

### 2.1 Climatic zones

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

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

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

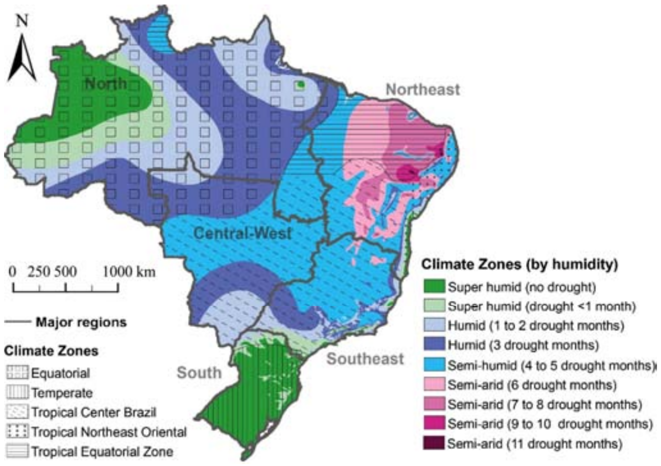


Figure 2 Location of major climate zones and humidity climate zones relative to the five major geographic regions of Brazil[31]

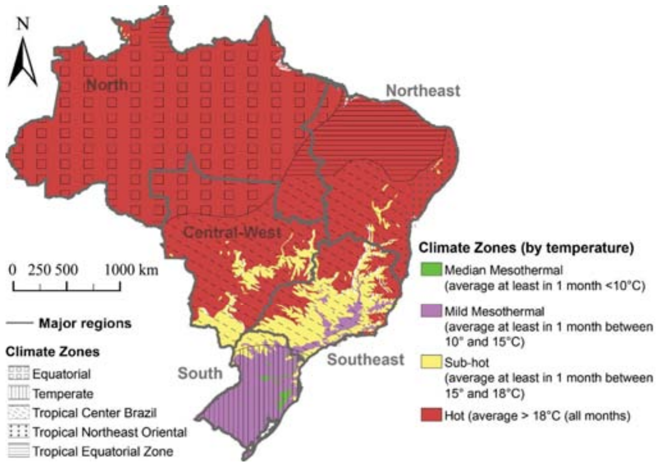


Figure 3 Location of major climate zones and temperature climate zones relative to the five major geographic regions of Brazil[31]

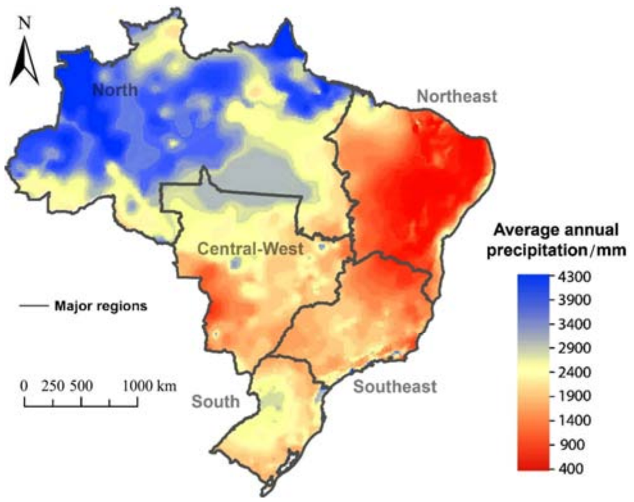


Figure 4 Distribution of mean annual precipitation relative to the five major geographic regions of Brazil[32]

## 2.2 Discharge characteristics

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

## 2.3 Soil types

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

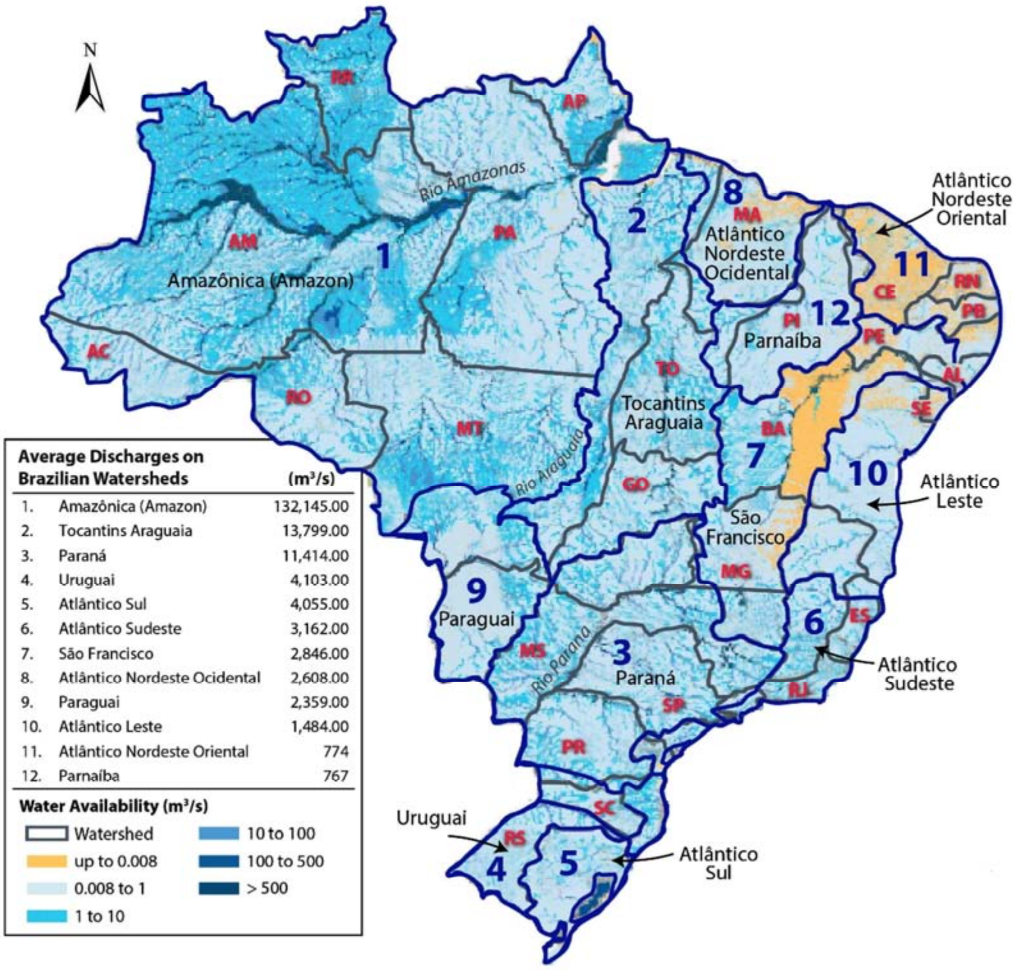


Figure 5 Spatial distribution of surface water availability by 12 major river basins or drainage regions and micro-basins within each the 12 major river basins or regions[30]

National-scale soil maps have been developed which show the distribution of major soil types across Brazil[39,40]. A Brazilian System of Soil Classification (SiBCS)[40] has also been developed that is based on previous regional soil surveys and features various texture, chemical and other soil-related characteristics[40,41]. The Brazilian Agricultural Research Corporation (EMBRAPA) has also compiled soil property data from surveyed soil profiles within the Brazilian Soils Information System which has recently been made available on-line (see Section 5 and Appendix A). In spite of these efforts, refined soil surveys that describe specific soil series and integrate soil pedon data more directly with corresponding landscapes remain scarce for most Brazilian subregions[37]. This lack of detailed soil maps has potential implications for applications of SWAT and similar ecohydrological models in Brazil.

## 3 Overview of surveyed SWAT applications in Brazil

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

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

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

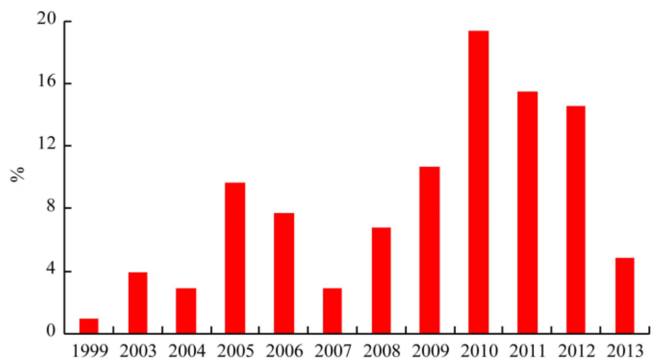


Figure 6 Distribution of the 102 studies identified in the Brazilian SWAT literature in percentage per year during the 14-year survey period (January 1999 to March 2013)

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


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

Figure 8 shows the percentages of SWAT studies performed per Brazilian region (8-a), state (8-b), type of simulation (8-c) and watershed drainage area (8-d). The highest concentration of SWAT publications (34%) was for watersheds in the South region of Brazil, composed by the states of Paraná (PR), Santa Catarina (SC) and Rio Grande do Sul (RS) (Figure 1 and 7), with a corresponding distribution of 8%, 24% and 8%, respectively (Figure 8-b). The second largest number of published studies (28%) of SWAT applications was in the Southeast region, which includes the states of Espirito

Santo (ES), Minas Gerais (MG), Rio de Janeiro (RJ) and São Paulo (SP). The remaining 38% of SWAT studies were published for applications in the Northeast (22%), Central-West (10%) and North regions (1%), with only one study published in the North region.

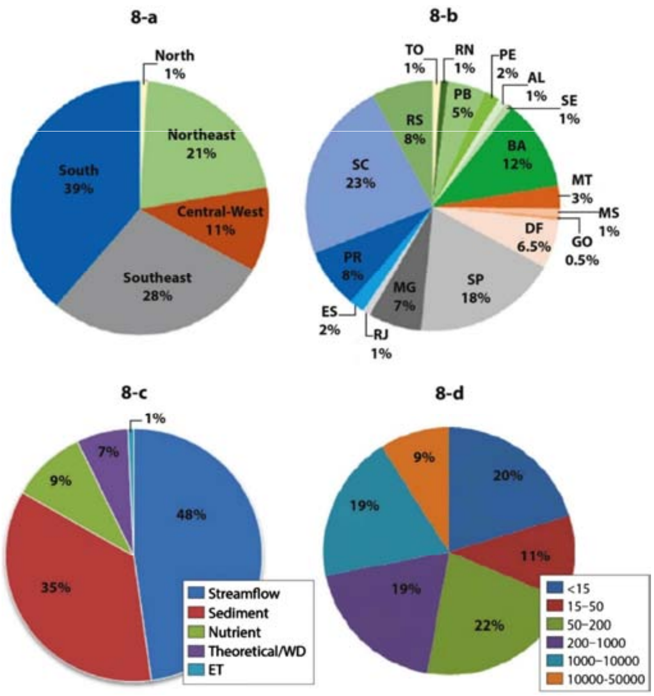


Figure 8 Percentage of publications using SWAT by: region (8-a), state (8-b), type of simulation (8-c) and watershed drainage area (8-d)

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

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

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

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

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

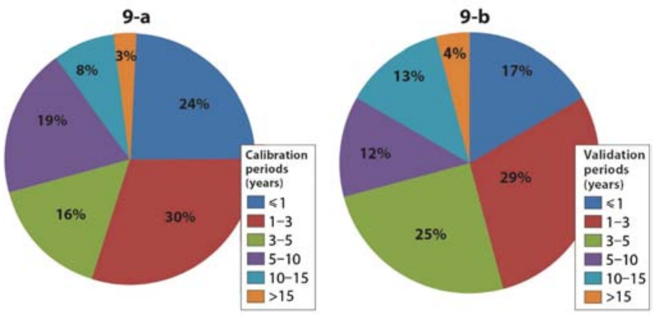


Figure 9 Distribution of studies, which reported calibration or validation results, based on time periods used for (a) calibration and (b) validation

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

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

| Performance Rating[a] | NSE criteria[a] | Monthly NSE (31 studies) | Daily NSE (26 studies) |
|---|---|---|---|
| Very Good | 0.75<NSE≤1.00 | 61% | 25% |
| Good | 0.65<NSE≤0.75 | 29% | 18% |
| Satisfactory | 0.50<NSE≤0.65 | 3% | 25% |
| Unsatisfactory | NSE≤0.50 | 6% | 25% |

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

### 3.1 Further insights regarding the surveyed Brazilian SWAT literature

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

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

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

## 4 An in-depth look at recent English Brazilian SWAT literature

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

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

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

Note: [a] See Figure 1 for locations of each respective state. [b] Watershed size not reported. [c] Drains portions of the states of Minas Gerais, Bahia, Pernambuco, Alagoas, Sergipe, Goiás and the Federal District.

### 4.1 SWAT hydrologic testing

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

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

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

### 4.2 SWAT pollutant loss testing

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

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

**Table 3 Selected statistics for the studies (Table 2) that reported baseline sediment testing results**

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

Note: [a] NSE = Nash-Sutcliffe modeling efficiency[159,160]. [b] See previous studies[173,174] for further description of the modified SWAT model. [c] Five daily and monthly NSE statistics were computed for each of five years. [d] Five statistics were computed for four different precipitation sources and the ensemble mean of the individual predictions.

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

### 4.3 Overview of scenario results

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

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

A SWAT BMP assessment of terrace, sediment retention basin and multi-diverse crop rotation impacts on streamflow and sediment transport was performed for the Pipiripau River watershed[141] using the same precipitation input ensemble as described above[128].

The authors modified SWAT in order to more accurately account for the use of small sediment retention basins that are typically installed along roads to capture surface runoff and sediment. The results for the ensemble mean varied greatly as highlighted by the following three scenarios[128,141]: (1) adoption of a complex 8-year rotation with 11 different crops on 50% of the cropland resulted in streamflow and sediment reductions of 43% and 21%, (2) installation of terraces on 100% of the agricultural areas resulted in streamflow and sediment reductions of 0.6% and 31%, and (3) implementation of sediment retention basins along 100% of the road network resulted in streamflow and sediment reductions of 0.06% and 22%.

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

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

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

## 5 Brazilian databases for SWAT applications

Many of the studies reviewed here described difficulties in applying SWAT for Brazilian watersheds due to a lack of data availability, a lack of easily accessible forms of data that have been compiled and/or problems related to the processing of data required for the model application[16,42,45,54,57,58,65,83,84,90,116,117,120,135,157]. Much of the existing data is not well organized, is not accessible via centralized databases or exists in formats that are not readily useable in the ArcSWAT Geographic Information

Systems (GIS) interface[177] or other pre-processing tools that are used to build SWAT input data sets. The lack of available data or easily accessible data at the required precision, quality and resolution is a particularly acute problem for certain subregions of the country (e.g., Amazonia; Figures 1). These data constraints result in the need to perform theoretical parameterizations for many SWAT applications in Brazil. An example of such parametrizations is the use of pedo-transfer functions in many studies to estimate parameters of Brazilian soils to run SWAT.

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

Tables 4 to 7 present global, national, state and other sources of climate/hydrological, digital elevation map (DEM), land use and soil data that are available to support SWAT applications in Brazil, along with example studies that report using the various data sources. It is expected that this overview of data sources will serve as a useful resource for scientists and others who already are using SWAT, or plan to use the model in the future, in Brazil. Brazil also has a federal law (Law 12527 of 2011) that regulates the right to obtain public information; thus if a certain study or station belongs to a government agency, information for that study can be accessed via an "Access to information" request[180]. Weblinks are provided in Appendix A that provide internet locations where interested potential users can either access data directly or learn more about the how to obtain various data from government agencies and other sources.

**Table 4 Climate and hydrological data sources for Brazilian SWAT applications**

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

Note: [a] See Figure 1 for locations of specific states within Brazil.

**Table 5 Digital Elevation Map (DEM) data sources for Brazilian SWAT applications**

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

Note: [a] See Figure 1 for locations of specific states within Brazil. [b] A SRTM version also exists that has been corrected by EMBRAPA for Brazil (see Appendix A).

**Table 6 Land Use Map data sources for Brazilian SWAT applications**

| Institution/Agency | Extent of coverage[a] | Example studies reporting use of data |
|---|---|---|
| USGS (United States Geological Survey - Land Cover Dataassemble several links to data sources) | Global | ---- |
| FAO (Food and Agriculture Organization) Global Land Cover-SHARE (GLC-SHARE) | Global | ---- |
| INPE (National Institute for Space Research)[182,183] | São Paulo | ---- |
| Bahia State Company of Urban Development | Bahia | 97 |
| IAC (Agronomic Institute of Campinas) | São Paulo | 55 |
| FATMA (Environmental Foundation)[184,185] | Santa Catarina | 90, 98 |
| PARANASAN project[186] | Paraná | 34, 45 |
| LANDSAT satellite images | Global | 42, 45, 47, 52-54, 65, 78, 79, 83, 88, 95, 128, 130, 136 |
| SPOT satellite images | Global | 43, 44, 64, 68, 82 |
| Orthophotographs | Global | 73, 75 |
| IKONOS satellite images associated with field surveys | Global | 102 |
| Produtor de Água project[187] | Pipiripau River Basin | 141 |
| Field Surveys | Local | 81 |
| From previous studies | Local | 49, 50, 59, 61 |

Note: [a] See Figure 1 for locations of specific states within Brazil.

**Table 7 Soil Map and properties data sources for Brazilian SWAT applications**

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

Note: [a] See Figure 1 for locations of specific states within Brazil.

## 6 Future research needs and directions

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

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

2) Risk Assessments & Disaster Management for Drought, Floods and Landslides: Droughts and floods represent the main impacts of extreme hydrometeorological situations in Brazil, affecting both populated areas and ecosystems[191,192]. The Brazilian Northeast suffers from recurrent droughts, which are often followed by floods[193], including a prolonged drought during 2010 to 2013 which was the worst drought in recent decades[194]. Droughts and floods are also part of the natural climate variability in the North Region of Brazil (Amazon), where the most intense

droughts and floods in recent history have occurred in the last 10 years[192]. A recent drought in southeast Brazil (2014-2015) has resulted in the lowest observed river flows of the last 3 decades and water supply reservoirs for the São Paulo Metropolitan region having their dead volume being pumped[195-197]. Floods meanwhile represent 58% of the environmental disasters in Brazil[198]. These developments are consistent with the hypothesis that extreme droughts and floods have become more frequent and intense[199], and could amplify in the future[192]. Therefore, future hydrological modeling with SWAT in critical areas in Brazil combined with risk assessments, can lead to better preparedness and adaptation measures to reduce loss of life, property, crops, etc., and could lead to improvements in the sub-daily component of SWAT[200], the use of SWAT as a forecasting system for predicting the probability of floods and long-term probability of droughts, and other improvements.

3) Better Vegetation Representation (Parameters and Routines): Much of the typical natural vegetation represented by different Brazilian biomes (Figure 1) and many Brazilian crops are not currently included in the SWAT plant parameters database. Some studies have adapted or used other plant parameters already available in the database to represent different crops[158]. According to a previous SWAT review study[10], there is a need to expand the plant parameter database to support a greater range of vegetation that can be simulated with the model and a need to perform more extensive testing of the crop components, including revisions to crop parameters where needed. This is further confirmed by the work performed for the Santa Maria/Torto watershed (Table 2)[130], which showed that the modified SWAT crop growth component more accurately replicated growth characteristics of tropical perennial vegetation and allowed for more flexibility in simulating leaf area index (LAI), which typically fluctuates less over different seasons compared to North American vegetation growth patterns.

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

5) NWRP and Brazilian Forest Code: As noted previously, the Brazilian NWRP[1,2] has established bold sustainability, integrated management and safety objectives. Specific tools are available for implementing this policy such as: water resources plans, classification of water bodies in different “use classes”, a permit system for water withdrawal and use, water pricing, and a water resources information system[1]. Recent changes in the Brazilian Forest Code (BFC)[202] policy, which was first created in 1965 and modified most recently in 2012, have generated considerable controversy and also have important water resources implications. The original BFC required conservation (Legal Reserve) of 80% of the native property area in the Amazon region and 20% in other biomes (Figure 1), and also designated Areas of Permanent Preservation (APPs) to preserve environmentally sensitive areas, which include riparian preservation areas and hilltop preservation areas (high elevations and steep slopes). The new BFC maintains the Legal Reserve and riparian preservation area conservation requirements, and establishes new mechanisms that may result in enhanced provision of ecosystem services[202]. However, the revised BFC also reduces the hilltop preservation areas (reducing total area by 87%) and restoration requirements, and provides amnesty for pre-2008 illegal deforestations. Thus, there is an urgent need to use SWAT to evaluate the implications of adopting the NWRP and/or BFC for specific watersheds.

6) Watershed-Scale Water Quality studies: As previously described, the majority of surveyed Brazilian SWAT studies have focused on just hydrologic/

streamflow analyses. Thus expanded water quality research of sediment, nutrient and other pollutant transport with SWAT is an important future research need, to better understand the implications and impacts of both point source and diffuse source pollution. This can potentially lead to better process understanding in different regions and conditions, even though detailed observed water quality data is scarce in some regions of Brazil. A broader SWAT water quality research emphasis will also support expanded scenario investigations such as evaluation of agricultural practices, determination of critical source areas and other possible water quality scenarios.

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

8) Bioenergy Crops Studies: At present, large areas of Brazil are devoted to short-rotation eucalyptus and sugar-cane crops for energy purposes[203], and production of biodiesel fuels from vegetable oils has also recently begun. Brazil is currently the largest producer, consumer and exporter of ethanol[204]. Eucalyptus wood is converted in charcoal for the Pig iron and Steel industry. Sugar cane is primarily used for ethanol production and has two key by-products: bagasse, which is used for electricity production or the production of biodegradable plastic, and vinasse (stillage) which is mainly used for fertigation. Therefore, SWAT studies focused on hydrological and water quality impacts of bioernergy crops in Brazil are needed to assess the implications of the growing biofuel industry, which may benefit a range of different sectors.

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

## 7 Conclusions

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

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

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

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## Appendix A Internet locations for the majority of data sources listed in Tables 4 to 7

| Institution/Agency | Internet location of data source |
|---|---|
| **Climate/hydrological data sources** | |
| NCEP-CFSR (National Centers for Environmental Prediction - Climate Forecast System Reanalysis) | http://globalweather.tamu.edu/ |
| INMET (National Institute of Meteorology) | http://www.inmet.gov.br/projetos/rede/pesquisa/ |
| EMBRAPA (Brazilian Agricultural Research Corporation)[a] | https://www.embrapa.br/en/home |
| SIMEPAR (Paraná State Meteorological System)[a] | http://www.simepar.br/site/internas/conteudo/produtos_servicos/pesquisa.shtml |
| UNESP (State University of São Paulo) | http://www.ipmet.unesp.br/ |
| UFMT (Federal University of Mato Grosso) | http://200.129.241.80/desa/estacaomestrebombled.html |
| Battistella Florestas Company[a] | http://www.battistella.com.br/ |
| Coruripe Plant[a] | http://www.usinacoruripe.com.br/ |
| Epagri/Ciram (Santa Catarina Agricultural Research and Extension[a] Corporation) | http://ciram.epagri.sc.gov.br/ |
| USP (University of São Paulo)[a] | http://www.estacao.iag.usp.br/<br>http://www.leb.esalq.usp.br/postoaut.html |
| ANA (National Water Agency) | http://hidroweb.ana.gov.br/ |
| ANEEL (Brazilian Electricity Regulatory Agency)[a] | http://www.aneel.gov.br/ |
| DAEE (Department of Water and Electrical Energy) | http://www.hidrologia.daee.sp.gov.br/ |
| SABESP (Basic Sanitation Company of the São Paulo State)[a] | http://site.sabesp.com.br/site/Default.aspx |
| **DEM data sources** | |
| SRTM (Shuttle Radar Topography Mission) | http://www2.jpl.nasa.gov/srtm/dataprod.htm<br>http://www.relevobr.cnpm.embrapa.br/download/[b] |
| ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) | http://asterweb.jpl.nasa.gov/data.asp |
| IBGE (Brazilian Institute of Geography and Statistics - Topographic maps) | http://www.ibge.gov.br/home/geociencias/download/arquivos/index14.shtm |
| **Land use data sources** | |
| USGS (United States Geological Survey - Land Cover Dataassemble several links to data sources) | http://landcover.usgs.gov/landcoverdata.php |
| FAO (Food and Agriculture Organization) Global Land Cover-SHARE (GLC-SHARE) | http://www.glcn.org/databases/lc_glcshare_en.jsp |
| INPE (National Institute for Space Research)[a] | http://mtc-m19.sid.inpe.br/col/sid.inpe.br/mtc-m19/2013/07.01.12.41/doc/publicacao.pdf [168]<br>http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0102-77862013000200002[169] |
| Bahia State Company of Urban Development[a] | http://www.informs.conder.ba.gov.br/produtos.asp |
| IAC (Agronomic Institute of Campinas)[a] | http://www.iac.sp.gov.br/jndmirim/ |
| FATMA (Environmental Foundation) | http://ciram.epagri.sc.gov.br/index.php?option=com_content&view=article&id=1172&Itemid=543 |
| LANDSAT satellite images | http://landsat.usgs.gov/ |
| SPOT satellite images | http://www.geo-airbusds.com/en/143-spot-satellite-imagery |
| IKONOS satellite images associated with field surveys | http://www.satimagingcorp.com/gallery/ikonos |
| **Soil map and property data sources** | |
| FAO-UNESCO (Food & Agriculture Organization- United Nations Educational, Scientific and Cultural Organization) | http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/ |
| Project RADAMBRASIL (Brazilian Government) | http://mapas.ibge.gov.br/tematicos/solos |
| EMBRAPA (Brazilian Agricultural Research Corporation) | http://www.sisolos.cnptia.embrapa.br/ |
| ISRIC (World Soil Information) | http://www.isric.org/data/data-download |
| IAC (Agronomic Institute of Campinas)[a] | http://www.iac.sp.gov.br/solossp/ |
| Emater-RS[a] | http://www.emater.tche.br/site/ |
| SEMA-Environmental State Foundation[a] | http://www.sema.mt.gov.br/ |
| Watershed Committee: Alto Paraguay Basin Conservation Plan[a] | http://www.mma.gov.br/port/se/pnma/ecos24.html |
| Integrated management project for the São Francisco Watershed supported by ANA[a] | http://cbhsaofrancisco.org.br/o-cbhsf/ |
| Water Resources Master Plan for Bahia State[a] | http://www.ana.gov.br/AcoesAdministrativas/CDOC/docs/planos_diretores/Bahia/plano_d |

Note: [a] The actual data sources may not be directly available on the web; however, the weblinks provided here provide a starting place to contact the responsible agency or person. [b] SRTM version that has been corrected by EMPRAPA for Brazil.