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IMPROVEMENTS IN SWAT MODEL FOR REGIONS WITH A MONSOON CLIMATE, HIGH POPULATION DENSITY, AND WATER SCARCITY: A CASE STUDY IN THE FEDERAL DISTRICT OF BRAZIL

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Co-orientador: Prof. Dr. Latif Kalin

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UNIVERSIDADE DE BRASÍLIA
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MELHORIAS NO MODELO SWAT PARA APLICAÇÃO EM REGIÕES DE CLIMA MONSONICO, ALTA DENSIDADE POPULACIONAL E ESCASSEZ HÍDRICA: UM ESTUDO DE CASO NO DISTRITO FEDERAL BRASILEIRO

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“Assim veio a mim a palavra do Senhor, dizendo: Antes que te formasse no ventre te conheci, e antes que saísses da madre, te santifiquei; às nações te dei por profeta.

Então disse eu: Ah, Senhor DEUS! Eis que não sei falar; porque ainda sou um menino. Mas o Senhor me disse: Não digas: Eu sou um menino; porque a todos a quem eu te enviar, irás; e tudo quanto te mandar, falarás. Não temas diante deles; porque estou contigo para te livrar, diz o Senhor.”

Jeremias 1:4-8

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MELHORIAS NO MODELO SWAT PARA APLICAÇÃO EM REGIÕES DE CLIMA MONSONICO, ALTA DENSIDADE POPULACIONAL E ESCASSEZ HÍDRICA: Um estudo de caso no Distrito Federal brasileiro

Autor: Welber Ferreira Alves

Orientador: Henrique Llacer Roig

Co-Orientador: Latif Kalin

RESUMO: A gestão dos recursos hídricos torna-se cada vez mais difícil e necessária, haja vista o cenário de indícios de mudanças/variações climáticas que tem ocorrido no Mundo e no Brasil, somado aos fenômenos de expansão demográfica e ocupação desordenada em áreas metropolitanas que acabam gerando conflitos por esses recursos e alterações em seu ciclo natural. O cenário de escassez hídrica no Brasil tornou-se mais comum na vida de muitos brasileiros, principalmente em grandes cidades como São Paulo e Fortaleza, e, mais recentemente, em Brasília, uma cidade planejada com pouco mais de 60 anos de fundação. Localizada no Centro-Oeste brasileiro, com sazonalidade climática bem definida, secas prolongadas e chuvas concentradas, a Capital brasileira vive diante desse cenário, despontando entre os anos de 2016 e 2018 para uma situação de estresse hídrico, que conduziu a várias ações como racionamento semanal e obras emergenciais para captação em novas fontes. Nesse sentido, tanto uma compreensão ampliada dos fenômenos hidrológicos, como também uma política de planejamento no uso desses recursos que permita a inclusão de análises hidrológicas mais representativas é de grande urgência. Diante desse quadro, urge a necessidade do desenvolvimento de sistemas/modelos que permitam ao tomador de decisões uma análise mais consistente da disponibilidade hídrica frente à atual e às futuras demandas, com o objetivo de fazer planejamentos exequíveis e sustentáveis. Este estudo pretendeu desenvolver melhorias no SWAT (Soil and Water Assessment Tool), um modelo hidrológico amplamente consagrado na literatura, a fim de que trouxesse melhores resultados nas aplicações de gestão de recursos hídricos em regiões de monções. As melhorias foram implementadas junto com o programa de calibração de modelos, SWAT CUP (SWAT Calibration and Uncertainty Program). Para tanto, o presente trabalho foi desenvolvido em quatro fases. A primeira verificou que, para a região e período estudados, não havia evidências significativas de tendência de redução ou aumento das chuvas, principalmente nas áreas de abastecimento humano. Foram analisados 21 pluviômetros, anualmente e em períodos hidrológicos (DJF, MAM, JJA e SON), por meio de quatro testes estatísticos: Mann-Kendall (MK), Cox-Stuart (CS), Spearman (SP) e Wald- Wolfowitz (WW). Os resultados gerais indicam que a percentagem de medidores / períodos apresentando tendências pelo MK foi de 10,48%, CS 9,52%, SP 12,38 e WW 8,57%. Além disso, apenas uma estação apresentou tendência de redução das chuvas no período DJF, e não está em uma região voltada para o abastecimento humano. Os demais pluviômetros que apresentaram tendência decrescente, apresentaram-no para o período JJA, que apresenta valores de chuva insignificantes para gestão hídrica. A segunda fase adaptou o módulo de gestão de reservatórios do SWAT à realidade de regiões que apresentam grande variabilidade no consumo humano. Isso é relevante, pois o SWAT aceita apenas o consumo médio mensal histórico de água. O modelo modificado obteve NSE de 0,71 para volume do reservatório em contraste com o uso do modelo padrão que obteve NSE de - 0,18, aplicado na bacia de Santa Maria. A terceira determinou a melhor fonte de dados de precipitação, bem como o padrão de distribuição para geração de dados hidrológicos para uso no SWAT. Foram utilizados dois pluviômetros (em três abordagens: em conjunto, apenas um e usando a média aritmética de ambos), buscando a melhor composição para a modelagem. Também foram verificados dois produtos de estimativa que combinam dados de satélite e estações terrestres, CHIRPS e MSWEP. CHIRPS, MSWEP e a média aritmética das duas estações obtiveram um desempenho “satisfatório” com base em NSE, R² e PBIAS durante a etapa de calibração. No entanto, para a etapa de validação, apenas o CHIRPS obteve um resultado “satisfatório” para as três funções objetivo. Os outros dois métodos falharam em relação ao R². As estações, tanto juntas quanto isoladas, não apresentaram resultados satisfatórios com o R² na calibração e apresentam baixo desempenho na validação. A quarta etapa fez duas adaptações no código-fonte do SWAT, alterando o método de cálculo do escoamento de base, além de incorporar a possibilidade de calibrar as abstrações iniciais para estimar o escoamento superficial, utilizando o modelo SCS-CN. O modelo acoplado com essas duas modificações demonstrou melhor desempenho na previsão de vazão para uma bacia hidrográfica de monção coberta por vegetação de cerrado. As Modificações permitiram uma representação mais realista e precisa dos processos físicos presentes na bacia do Rodeador. Embora tanto o modelo de fluxo de base, quanto aquele que permite a calibração das abstrações iniciais, individualmente, tenham mostrado benefícios para a bacia estudada, o modelo combinado apresentou melhores resultados. A título de comparação, o modelo contendo as duas modificações apresentou NSE de 0,66 para as duas etapas de análise (calibração e validação), enquanto o modelo padrão apresentou 0,59 e 0,57, respectivamente. Com relação ao índice de verificação das simulações realizadas, o fator p, o modelo combinado obteve 0,93 e 0,85, enquanto o modelo padrão registrou 0,39 e 0,34, tanto para as etapas de calibração quanto para verificação, respectivamente. Em última análise, a tese também apresenta, uma proposta de sistema de gestão de recursos hídricos focado na otimização dos recursos hídricos, auxiliado pelas mudanças desenvolvidas no modelo hidrológico SWAT, para regiões com a sazonalidade climática acima mencionada. O sistema segue um fluxo de trabalho em que o usuário é responsável por inserir principalmente dados climáticos, consumo de água e uso / cobertura do solo, que convergem para disponibilizar os resultados em um painel. Através da integração destes dados, bem como as melhorias desenvolvidas no SWAT, este projeto também visa apresentar uma proposta de um sistema eficaz de gestão dos recursos hídricos, permitindo a criação de possíveis cenários e desenvolvimentos futuros, tanto de natureza hidrológica, considerando possíveis longos períodos de escassez, bem como fatores sociais, como o crescimento populacional e / ou mudança de hábitos de consumo.

Palavras chave: Modelagem, SWAT-CUP, Hidrologia

IMPROVEMENTS IN SWAT MODEL FOR REGIONS WITH A MONSOON CLIMATE, HIGH POPULATION DENSITY, AND WATER SCARCITY: A CASE STUDY IN THE FEDERAL DISTRICT OF BRAZIL

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ABSTRACT: Management of water resources is becoming increasingly challenging and necessary, due to growing evidence of climate variations around the world, including Brazil. This disruption to natural water cycles along with demographic expansion, and often disorderly occupation in metropolitan regions, has resulted in conflicts over these resources. Water scarcity in Brazil has become a reality for many Brazilians, especially in larger cities such as São Paulo and Fortaleza, and more recently in Brasília, the planned capital city just over 60 years old. Located in the midwest of the country and with well-defined climatic seasonality, punctuated by prolonged droughts and concentrated rains, the capital city has emerged through 2016 and 2018 years as a water stressed location, resulting in various actions such as water rationing, and emergency projects aimed at the capture of new sources. This situation urgently requires both a amplified understanding of hydrological phenomena, as well as a planning policy for the use of these resources with the inclusion of more robust hydrological analyses. In light of this situation, systems must be developed that enable decision-makers to more consistently analyze water availability based on current and future demand, and that results in more feasible and sustainable planning. This study intended to develop improvements in SWAT (Soil and Water Assessment Tool), a hydrological model ingrained in the literature, in order bring better results in water resources management applications in monsoon regions. The improvements were associated along with the model's calibration program, SWAT CUP (SWAT Calibration and Uncertainty Program). To this end, the present work has developed in four phases. The first verified that, for the studied region and period, there was no significant evidence of reduction trends or increase in rainfall, principally in areas used for human supply. Twenty-one rain gauges were analyzed, both annually and in hydrological periods (DJF, MAM, JJA and SON), using four statistical tests: Mann-Kendall (MK), Cox-Stuart (CS), Spearman (SP) and Wald-Wolfowitz (WW). The

overall results indicate that the percentage of gauges/periods displaying trends by the **MK** was 10.48%, **CS** 9.52%, **SP** 12.38, and **WW** 8.57%. Besides, only one station showed a tendency for rainfall reduction in the DJF period, and it is not in a region focused on human supply. The other rain gauges that showed a decreasing trend, presented it for the JJA period, which presents insignificant rain values related to water management. The second phase adapted the SWAT hydrological reservoir module to the reality of regions that have high variability in human consumption. This is relevant since SWAT does accept only historic average monthly water consumption. The modified model achieved NSE of 0.71 for volume of the reservoir in contrast to the use of the standard model that obtained NSE of - 0.18, applied in Santa Maria basin. The third determined the best source of rainfall data as well as the distribution pattern for generation of hydrological data for inclusion in the SWAT model. Two rain gauges were used (in three conditions: together, only one, and using arithmetic mean), seeking the best composition for the modeling. It was also verified two estimation products that combine satellite data and ground stations, CHIRPS and MSWEP. CHIRPS, MSWEP, and arithmetic mean of the two stations achieved a “satisfactory” performance based on NSE, R^2 and PBIAS during the calibration step. However, for the validation step, only CHIRPS achieved a “satisfactory” result for the three objective functions. The other two methods failed with respect to R^2. The stations, both together and isolated, did not show satisfactory results using R^2 in the calibration, and present low performance in the validation. The fourth made two adaptations to the SWAT source code, changing the method of calculating base flow, as well as incorporating the possibility of calibrating initial abstractions to estimate surface runoff, using the SCS-CN model. The coupled model demonstrated a better performance in the forecast of flow for a monsoon hydrographic basin covered by savanna vegetation. The Modifications allowed a more realistic and accurate representation of the physical processes present in the Rodeador basin. Although both the base flow model, as well as the one that allows the calibration of the initial abstractions, individually, have shown benefits for the studied watershed, the combined model showed better results. As a comparison, the model containing the two modifications presented an NSE of 0.66 for the two stages of analysis (calibration and validation), while the standard model presented 0.59 and 0.57, respectively. With respect to the verification index of the performed simulations, the p-factor, the

combined model obtained 0.93 and 0.85, while the standard model registered 0.39 and 0.34, both for the calibration and validation steps, respectively. Ultimately the thesis also presents a proposal of a water resource management system focused on optimization of water resources, aided by changes to the SWAT hydrological model, for regions with the above mentioned climatic seasonality. The system follows a workflow in which the user is responsible for inputting especially climatic data, water consumption and land use/land cover, that converges to make dashboard results available. Through integration of this data as well as the improvements in the SWAT model, the project aims to present a proposal of an effective system for the management of water resources, enabling creation of possible future scenarios and developments for both hydrological nature, considering possible long periods of scarcity, as well as social factors, such as population growth and/or changing consumption habits.

Keywords: Modeling, SWAT-CUP, Hydrology

FIGURE LIST

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LIST OF ACRONYM

95PPU – *95 Percent Prediction Uncertainty*
ADASA – *Agência Reguladora de Águas, Energia e Saneamento Básico do Distrito Federal*
ANA – *Agência Nacional de Águas e Saneamento Básico*
ArcSWAT – *SWAT Interface for ArcGIS*
BIAS – *Bias*
CAESB – *Companhia de Saneamento Ambiental do Distrito Federal*
CHIRPS – *Climate Hazards Group InfraRed Precipitation with Stations*
CN – *Curve Number*
CS – *Cox-Stuart trend test*
CSI – *Critical Success Index*
DJF – *December, January and February*
DSS – *Decision Support System*
ET – *Evapotranspiration*
FAR – *False Alarm Ratio*
FD – *Brazilian Federal District*
GIS – *Geographic Information System*
GDF – *Governo do Distrito Federal (Brazilian Federal District Goverment)*
GDMS – *Geographic Database Management System*
HRUs – *Hydrologic Response Units*
IBRAM – *Instituto Brasília Ambiental*
IBGE – *Instituto Brasileiro de Geografia e Estatística*
IHA – *Indicators of Hydrologic Alteration*
INMET – *Instituto Nacional de Meteorologia*
JJA – *June, July and and August*
MAM – *March, April and May*
MK – *Mann-Kendall trend test*
MSWEP – *Multi-Source Weighted-Ensemble Precipitation*
NSE – *Nash-Sutcliffe Efficiency*
PBIAS – *Percent Bias*
Qmmm – Average of the monthly minimums
R2 – *Coefficient of determination*
RMSEc – *Centered Root Mean Squared Error*
SCS-CN – Soil Conservation Service - Curve Number Runoff method
SEMA – *Secretaria de Estado Meio Ambiente do Distrito Federal*
SON – *September, October and November*
SP – *Spearman trend test*
SR – *Success Ratio*
SRTM – Shuttle Radar Topography Mission
SUFI-2 – *Sequential Uncertainty Fitting* Version2
SWAT – *Soil and Water Assessment Tool*
SWAT-CUP – *SWAT Calibration and Uncertainty Programs*
WMO – *World Meteorological Organization*
WW – *Wald-Wolfowitz trend test*

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SUMMARY

The idea of this work originated in the water crisis experienced by the Federal District in the period from 2016 to 2018, in which there were low rainfall rates, added to a historical and rapid population expansion in the region, leading the main rivers and reservoirs of human supply to critical levels. At the time, a simple management system was developed, based on historical data of flow and rainfall, generating rule curves for each of the reservoirs. Because of the weaknesses observed related to the applied methodology, the inexistence of a more advanced and robust method, and the possibility that similar events may happen in the future, the need for changes in this system has become indispensable, mainly from a more detailed investigation on the rainfall distribution in the region. From the existing SWAT hydrological model, the necessary improvements associated to runoff, baseflow and reservoir operation for adaptation and adjustments to the study region were developed. Thus, the chapters that make up this study were developed to deal with these procedures, as well as with the deepening of the investigation concerning rainfall. This study improved hydrological management tools, especially in response to critical events in monsoon regions.

This thesis followed a structure focused on development of a proposal to a Water Resource Management System and is divided into chapters that address the system as a whole, and other chapters that have become articles dealing with individual parts of the system. The first three chapters are structural in the sense that they introduce the theme and describe the purpose of the system, thereby forming part of the group of chapters focused on the system as a whole. The remaining chapters, with the exception of the last, are articles developed during the research that detail elements that served to improve the proposed system. The last chapter and final considerations describe the system and are part of this group of structural chapters. Figure 0-1 details this structure.

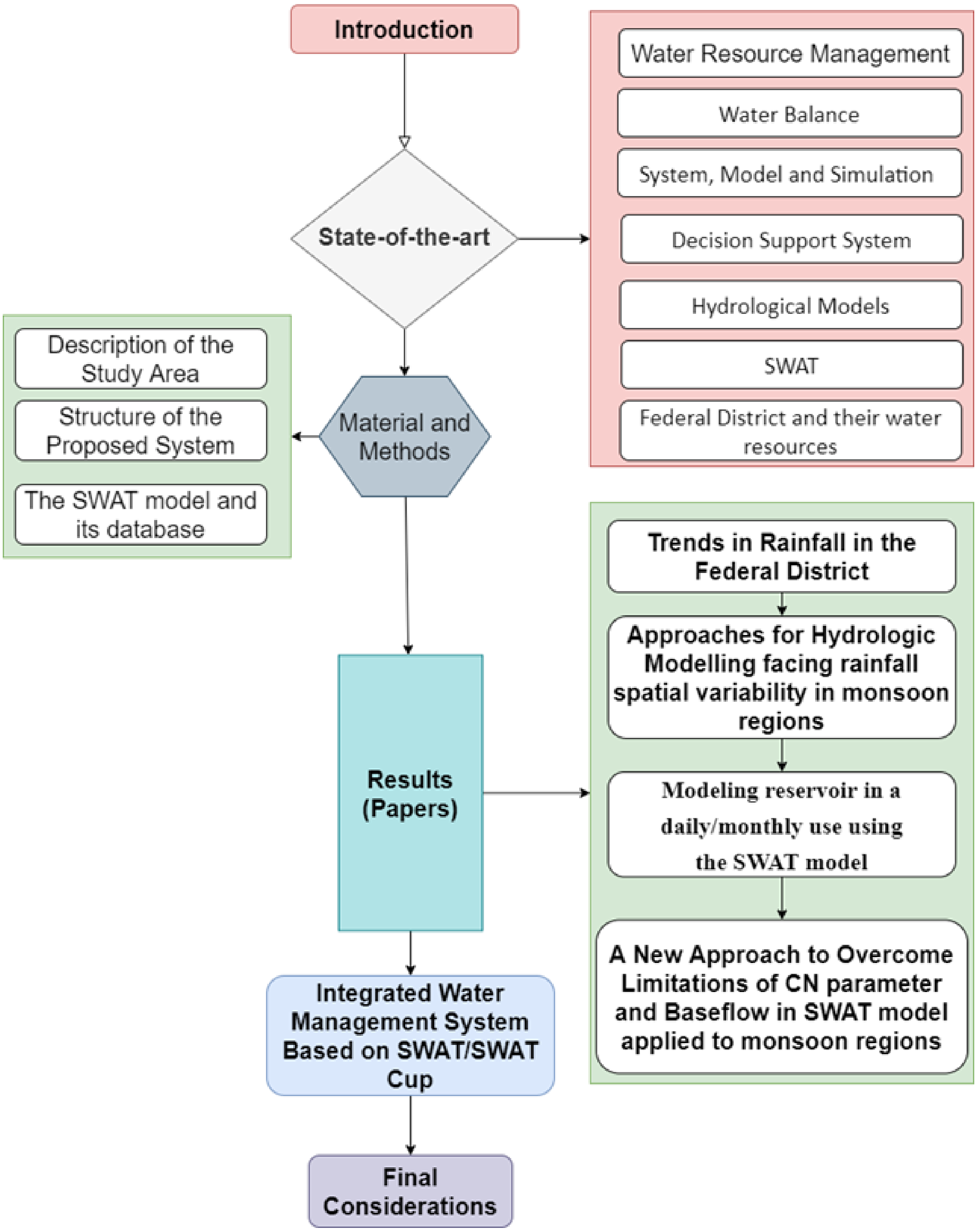

Figure 0-1: Thesis' structure

1. **INTRODUCTION**

Demand for water dates back to the earliest years of civilization and increases are usually associated with population growth and the necessities thereof (Biemans et al., 2011). Over the years, different types of demands for water resources have increased substantially and, despite growing need, water is a limited resource due to natural issues in space-time (Cirilo, 2015; Janssen, 1996; Telles, 2013; Tundisi, 2008).

Population growth, urbanization processes, and expansion of agricultural frontiers, for example, have resulted in increasing conflict over water resources, particularly in areas with multiple uses and low water availability (Tucci et al., 2001; UNWATER, 2015; USAID, 2017).

Conflicts over water use and availability become even more serious in regions with higher population density (Biswas & Gangwar, 2020; Kookana et al., 2020). Many urban centers, including some large Brazilian cities, have already experienced water scarcity events (ANA, 2016; Dziegielewski, 2003; Santos et al., 2012; Telles, 2013; Tundisi and Tundisi, 2015; UNWATER, 2015; USAID, 2017). Additionally, over the last several years, human activity and modifications to the environment have altered the water cycle, and these climate changes have brought with them a need for improved approaches to water resource management (Wang et al., 2018; Wu et al., 2013).

The situation described above presents a challenge for most institutions, directly or indirectly, related to the use and management of water resources, especially concerning reservoirs responsible for supplying cities as those principal water sources serve, both, human consumption and other purposes such as agriculture-related activities. These water stores, as well as their tributaries, end up suffering impacts related to anthropic action due to proximity to urban centers, particularly when urbanization happens in a disorderly way, leaving cities vulnerable to extreme hydrological events (UNWATER, 2015). This has been observed in water crises in São Paulo (Marengo and Alves, 2015), Rio de Janeiro (Targa & Batista, 2015) and in northeastern Brazil (Santos, 2012).

These consequences demand closer inspection of how changes caused by human actions affect the water balance in hydrographic basins and their impact on the dynamics of reservoirs associated with their multiple uses. Management of water resources undergoes a series of analyses that include economic, political, social, and environmental aspects (Pahl-Wostl, 2006; Su et al., 2020).

Over the past decades, mainly from the 1960s forward, use of hydrological models has gained prominence as a tool for supporting decision-making in water management (Fatichi *et al*., 2016). However, only rather recently, especially after the nineties, it was possible to achieve integrative management visions (space-time) for water resources, due to incorporation of geotechnologies, especially the Geographic Information Systems (GIS) and the Geographic Database Management System (GDMS) (Mckinney and Cai, 2002; Nagraj and Gosain, 2013; Tsihrintzis et al., 1996). This way, in following decades a sort of hydrological models were developed using GIS as essential support tool (Singh & Frevert, 2006). However, besides these general models, there is no universal model (WMO, 2009), each situation requires appropriate management processes tailored to the specifications of the region and that always consider global impacts, as previously pointed out by Christofoletti (1999).

In general, when looking at Latin America, water management still lacks this integrative approach, with the concept being very incipient or almost nonexistent in some countries, as pointed out by San Miguel (2018). This author also identified that Brazil has recognized the importance of water resource management, and by introducing related policies and adopting a national management system, stands out positively among other countries in the region in this regard. The creation of law 9.433 of 1997 (the Brazilian Water Law), which established national water resources policy along with the national water resources system was the beginning of an innovative process in the country, inspired by the French model of integration, based on economic and planning instruments (Veiga and Magrini, 2013). It brought together elements that helped with integration, such as management of each individual hydrographic basin, however fell short in considering how the management processes would effectively take place. The passage of this legislation must be recognized as a first and significant step towards the management of water resources in the country as suggested by San Miguel (2018).

In the Federal District of Brazil (FD), the chosen region for this study, there is an existing legal apparatus that replicates federal law, as well as a local regulatory agency responsible for management of water resources. The same way the water resource management system proposed by the federal law to Brazil, it is reproduced in the FD through water committees, environmental governmental institutions, and non-governmental organizations (LEI Nº 2.725, DE 13 DE JUNHO DE 2001)

There are some peculiarities in the Brazilian capital, that will be addressed later, citing as an example water availability associated with the low flows of its rivers, as well as its reservoirs (GDF and SEMA, 2012; Lima et al., 2018; Lorz et al., 2012). A clear discrepancy exists between their storage capacities when compared to other reservoirs that supply major capital cities (regions) in the country as São Paulo State and Ceará State. The water management process is correlated with usage grants, where the process for concession is based on statistical analysis of historical data of rivers, generating reference flows such as the Q_{90}, Q_{mmm}, and remaining flow that would represent the minimum amount of water of rivers should maintain. In this way, the quantity of water destined for the grants is subtracted from the reference flow so long as there is sufficient availability to meet the remaining flow (Distrito Federal, 15 de Agosto de 2017). Within this process, management seeks to satisfy users respecting human demands and environmental necessities. However, there is no integrated and dynamic vision of the hydrological cycle, as recommended by most modern management studies and processes (Pahl-Wostl, 2006; Su et al., 2020). Criteria are based solely on the history of registered flows, without considering future projections such as trends of the springs, either due to climatic variations or changes in land use. Nor do they consider projections of increased demand and are as such essentially static analyses. According to Stevović & Nestorović (2016), such approaches may lead to flawed decision-making in the water resource management process, as was made clear by recent water scarcity crises in Brazil (Marengo and Alves, 2015; Santos et al., 2012). The existence of a tool allowing for projection of future scenarios in accordance with reality and capable of adjusting for developments, such as the creation of new neighborhoods or eminence of climatological phenomenon such as *El Niño*, can be highly beneficial for the management of water resources in these large areas.

In order to better understand the situation in FD, it is worth mentioning again its current water storage capacity compared to, for example, the states of Ceará and

São Paulo where metropolitan regions have experienced recent crises. In Ceará State, the main reservoir (Castanhão), has a usable volume of 6.7 billion m³ to supply more than 4 million inhabitants (de Souza et al., 2017; IBGE, 2020; Pereira & Cuellar, 2015) and in São Paulo State, the Cantareira reservoir has 952 million m³ and supply 8 million inhabitants (SABESP, 2018). Conversely, FD holds a volume of 72 million m³ in the Descoberto reservoir, 61 million m³ in Santa Maria (GDF, 2017) and 7 million m³ in Paranoá Lake to supply 3 million inhabitants (the Paranoá Lake volume represents the average available volume based on legal restrictions)[1], representing much lower water storage capacity. This is an important element to consider, especially when confronting a lasting water scarcity situation, making this understanding fundamental to urban planning. This same analysis of water availability was undertaken by the United Nations Development Program (UNDP) for some countries in the world, correlating volume of water available with number of inhabitants. The study had, as an ideal parameter, an average annual value of approximately 1,700m³ per person to address agriculture, industry, energy, and the environment. Values below the ideal parameter were classified as worrying, following a scale in which below 1000m³ would represent scarcity, and below 500m³, absolute scarcity (UNDP, 2006). This study highlights the need to analyze volumes of water available to meet demands of the population. In Brazil, if we look at available volumes for each state needed to serve their respective metropolitan areas, and divide these volumes by their estimated populations for 2018, the water availability per inhabitants is 97 m³ (1,944 hm³/21 million inhabitants - SABESP, 2018) for São Paulo State and 3,700 m³ (11,351 hm³/3 million inhabitants - Funceme and COGERH, 2018) for Ceará State. Based on this information São Paulo can be classified as a location with absolute scarcity, while Ceará appears to be in a better situation.

When this same analysis is carried out for the Federal District, based on the volume of its reservoirs (Santa Maria, Descoberto and Paranoá), a total of 140hm³, and an estimated population of 3 million inhabitants (IBGE, 2018), there is only 46 m³ of storage available per inhabitant. These estimates shine light on the precarious water situation in the Federal District. The same kind of analysis for example done in the

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[1] Paranoá Lake volume was obtained in other project linked to this research.

Middle East of Brazil would register volumes of 1,200 m³ per person, putting the Federal District in a more fragile situation than countries in that region. This presents decision-makers with a complex and urgent challenge as, in addition to this limited water storage capacity (GDF, 2017), there is estimated future population growth (IBGE, 2018).

Water scarcity has become more evident recently, with unprecedented phenomena compared to over 40 years of data, following 3 consecutive years with low rainfall index, around 2/3 of the average (GDF, 2017). This fact, associated with population growth of 1 million inhabitants in just 15 years (PDAD, 2015), has led to an unprecedented water crisis in the capital and led to government actions such as implementation of contingency tariffs, pressure reduction in pipes, weekly rationing, emergency construction of new pipelines, reactivation of small water collection systems, emergency abstraction from an urban lake (Paranoá Lake), and the acceleration of a capture project from a reservoir in the neighboring State of Goiás (the Corumbá IV reservoir projected to finish in 2021, but as of yet not materialized, when it is estimated to supply 2.800 L/s and their volume is 3700 hm³) (CAESB, 2020, CORUMBÁ S. A., 2021; GDF, 2017).

Given these issues, it is clear that development of an integrated water resource management system is becoming increasingly important as a way of planning and implementing public policies to avoid or mitigate crises.

The use of hydrological models, especially computational mathematical ones, has developed into important tools for decision-making in crisis scenarios (Fatichi *et al*., 2016). There does, however, exist a knowledge gap between the management process and understanding of computational hydrological models, demonstrating a lack of integration as reinforced by Basco-Carrera et al. (2017). The authors point out that much research has been done to engage the various actors involved in the decision-making and planning process, however, not much has been done on how to integrate computationally based models into this participatory process. This is further corroborated by the analysis of Loucks et al. (2005), in which a gap was also found between what researchers in water resource modeling produce and what managers find useful. For sufficient, integrated analysis in the management process, multidisciplinary integration is needed, combining various expertises to configure and prepare future scenarios, as well as the ability to easily understand them. As Swain et al. (2015) highlighted, even though many participants in this process understand the results of hydrological modeling, they sometimes lack capacity to elaborate on these configurations. Loucks et al. (2005) summarized the need for this convergence between academia and resource managers, pointing out that when objectives are not clear and there is not sufficient scientific understanding of proposed questions, practical application of sophisticated methodologies and mathematical models may fall short.

This research aims to do improvements on SWAT model that permits the development of an integrated system allowing for management of water resources, utilizing both time-based geographic databases (space-time), as well as a water balance model. In this way, the proposed system can facilitate more efficient management of water resources, enabling decision-makers to make better, reality-based, decisions.

A series of procedures were developed in order to build the proposed system. First, the SWAT model was chosen as the hydrological model to be used, particularly because of its robustness (Bressiani et al., 2015a; Gassman et al., 2014; Tan et al., 2019) and the fact that various studies have been developed previously in the Federal District (Castro, 2013; Ferreira and Uagoda, 2016; Ferrigo et al., 2011; Ferrigo, 2014; L. de A. Salles et al., 2018). Second, there was a necessity to build a local geodatabase related to soils and plant characteristics as a basic input for the SWAT model. This yielded better performance for the SWAT model (Lima et al., 2013; L. de A. Salles et al., 2018; Strauch and Volk, 2013; Teodosiu et al., 2009). Some other studies were used to help in this process (Ferrigo, 2014; Lima et al., 2013; Maia et al., 2018; Reatto et al., 2003; Strauch and Volk, 2013).

Next, an analysis was performed on a series of rainfall data (21 rain gauges spread throughout the Federal District) in order to provide information about the presence of trends or lack thereof. The results identified some decreasing trends. This observation should be considered when generating future scenarios. A comparison was made between rain measure datasets and remote sensing data (CHIRPS and MSWEP). CHIRPS produced better results, however, the study showed that, depending on the application, a different set of rain measurements may yield better performance.

The SWAT model was then modified to allow for variations throughout the simulation period concerning withdraws in the reservoir. The default method, that assumes average monthly demand is constant during all simulated years, was substituted for an approach where the decision-maker can test different demand values for each day or month for all analyzed years.

Finally, the monsoon conditions observed in the Federal District and the interactions with the SWAT model were evaluated for groundwater and surface flow. Three modified versions of the SWAT model were developed in order to asseverate good agreement between observed and simulated streamflow. The version that used a modified recharge function and a new approach for the Curve Number Method (SCS-CN), produced significant improvements and should be considered in the application of the SWAT model for this region.

All these studies were fundamental in designing the proposed system which should meet the needs of the Federal District related to water management process (WMO, 2009a).

This study was guided by the hypothesis that an integrated system developing hydrological modeling based on data distributed within the local reality will allow for calculation of water balance in a more appropriate way resulting in more efficient management of water resources. This process should consider in a dynamic perspective water offers and demands of a given region combined with more detailed knowledge of variables impacting the hydrological system and water balance.

Brazil’s capital city, the chosen area of study, experienced critical water crises in recent years and prompt solutions were developed in order to provide information to decision-makers (Barcellos et al., 2018; Mello et al., 2018). In the present study, besides the improvements in the renowned SWAT model, a new DSS was proposed utilizing the cited model and the optimization program SWAT Cup in order to improve water management for the city. The proposed system incorporates both solutions in an integrated approach considering generated streamflows and reservoir volumes. Of principal focus for this project lies in the quest for the reduction of the gap between theory and application found in many models around the world (Becker and Serban, 1990).

1.1. Objectives

The general objective of the study was to develop improvements in SWAT model to enhance its application in monsoon climate areas, having high population density and water scarcity. Also, it was designed a conceptual model related to a system based on hydrological modeling to be used in the water resource management process that can be applied across different regions. This system aims to adapt the model to local specificities, as well as provide an analysis of the region's water balance, in order to contribute to generation of robust indicators that, when associated with future scenarios, will assist in planning and management of these resources.

Specific objectives of this research were:

- Analyzing the precipitation series available for the region;
- Analysis of ideal rainfall settings as data entry for regions with low density of monitoring stations;
- Adaptation of the SWAT model to the local reality regarding use of reservoirs in simulations;
- Adaptations to hydrological calculations of the model referring to surface flow and baseflow.

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2. STATE-OF-THE-ART

As previously mentioned, management of water resources goes through a series of analyses that involve economic, political, social, and environmental aspects, and over the last several decades, beginning principally in the 1960s, use of hydrological models started to gain prominence as a support tool for decision making (Fatichi *et al.*, 2016). As Abbott and Refsgaard (1996) suggested, water resources management based on scientific tools and efficient technologies is required as water resources challenges increase. This review sought to discuss the state of the art by analyzing three major areas: management of water resources as a whole, making use of international examples and their application in Brazil; the methodological principle that guides this management, based mainly on the concept of water balance; and the hydrological models themselves. In addition to these three themes, characterization of the study area was also done, focusing on main sources used for human supply.

2.1. Management of water resources

The main subject of this work is the management of water resources, whose guiding principle is balancing both management of multiple demands and water supplies (Munoz, 2000). Therefore, it is necessary to look at current management of water resources. Regarding international management of water resources, during the 8th World Forum event that took place in Brasilia in March 2018, the author of this work along with representatives from other participating nations sought to verify how this management took place in different countries. In general, there were solutions associated with climate forecasting such as the Flood Forecast System used in the Netherlands with focus on integrating climate predictions into warning systems (Kroos & Slomp, 2017; Verlaan et al., 2005). Governmental solutions were observed, as in eWater Source, a hydrological modeling platform used in Australia, where the focus is on integrating water resource management with public policies and governance capacity (Australian Goverment: Bureau of Meteorology, 2021; Carr & Podger, 2012; Rassam et al., 2013). Another governmental solution, K-water Hydro Intelligente

Toolkit (K-HIT), was presented by South Korea, as a proposal for total integration, bringing together several platforms, from dam operation and power generation to monitoring and warning stations (Integrated Water Resources Management Dept., 2021; Yi et al., 2020). Around the world it is possible to find so many other solutions. Thailand also developed a system, Thailand 4.0, where the model development plans adhere to the principle of integrated river basin structures and sustainable water management, taking into account government policies and national economic and social development plans (Apipattanavis *et al.*, 2018). Some efforts also can be found in South Africa, Burkina Faso, India, and Peru (Everard et al., 2021; Nkosi et al., 2021)

For a broader look at water management in other countries, especially with a focus on Latin America and Europe, it is recommended to read the work of San Miguel (2018), who sought to produce a more detailed analysis of both continents, comparing their developmental stages. And Araújo et al. (2015), where it was focused in Rio de Janeiro and Portugal. Also, it is recommended Cosgrove & Loucks (2015) and Kumar (2015), where it is analyzed in both works needs and challenges about water management around the world.

With respect to Brazil, at first glance it is important to highlight the Brazilian water law, law no. 9.433/1997 (Brazil, 1997), laying out some principles of water resource management in the country. This legislation has significantly increased the country’s concern and the policy instruments for water resources, representing a major advance for the period, particularly due to the institution of several tools aimed at management of water resources. As an example, we can mention management of demands from a multiple-use perspective, prioritization of human consumption; the use of the hydrographic basin as foundation for implementation of policies and planning, depoliticization of the issue; implementation of the water use right grant, which transfers responsibility for water management to management bodies.

Despite these advances, this important law faces some problems (Veiga and Magrini, 2013), such as the fact that water management is purely and strictly related to the topographic limits of the basin. In hydrology, hydrographic basin defines an area where all rainwater, as well as all surface and underground contributions, tend to converge on the same point (Tucci, 2005). However, this information is imprecise, given that underground conformations may have divisions that are not visible and superficial contributions may be affected by human actions. (Loucks et al., 2005). The urbanization of basins also changes the hydrogeological and geometric characteristics of a basin, whether due to the waterproofing of the soil or the construction of works such as rain drains, effluent transport ducts, and human supply systems, where distribution of water originating at these points is due to a water system that does not prioritize the return of water to the bodies, where they would naturally be related. As a result, the water measured at the convergence point of the basin, taking into account topographic formation and flow of rivers in the region, may not be as expected. Another point worth highlighting is the fact of omission in the sense of how control of use licenses should be granted. This has resulted in generation of several positions in the different Units of the Federation, and as a general rule granting according to availability in relation to flows reference and residual (Cardoso da Silva and Monteiro, 2004).

What stands out is, despite existing legal apparatus, the need for more dynamic and efficient management, given that many Brazilian municipalities are already suffering from some type of water scarcity. This can be seen in Figure 2-1, which shows the large number of cities affected by rationing actions throughout the year, that is, experiencing periods of water deprivation. This data was extracted from the SNIS (National Sanitation Information System) from the Ministry of Cities (2018), based on a 2008 survey, in which several challenges facing Brazilian municipalities, such as the absence of treated water, were verified by example. That said, tools to support decision-making can be instrumental in mitigating situations like this.

Despite the questions presented, Law 9.433 of 1997 was indeed an important step in the process of managing water resources in Brazil, providing general guidelines and instruments promoting guidance to both decision-makers and users. It should be noted that in Brazil, the national institution responsible for water management is the National Water Agency (ANA), however, it is only legally responsible for management of federal rivers, due to issues related to dominance present in the Brazilian Constitution. ANA also has the role of promoting management at the regional level, subsidizing the action of states and municipalities, but ultimately management of state rivers is the responsibility of local government in collaboration with basin committees formed by representant from all society sectors (ANA, 2011).

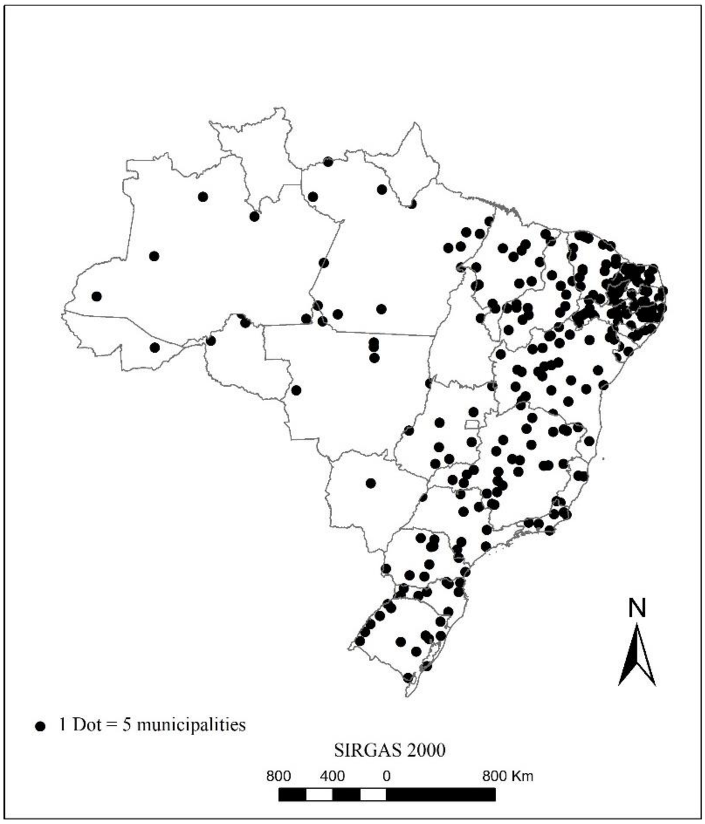


Figure 2-1: Number of municipalities by Federation Unit (UF) who undergo some type of rationing per year, based on data from SNIS (Ministry of Cities, 2018) and IBGE (2018)

Due to dominance issues and political divisions within the country, each unit of the federation chose different entities to manage water. In some states, this function is carried out by institutes and in others through environmental departments or, more specific water entities. With respect to the Brazilian Federal District, the institution responsible for managing water resources in the capital is the Regulatory Agency for Water, Energy and Basic Sanitation of the Federal District – ADASA (Distrito Federal, 2015). To implement the tools established by Law 9.433 of 1997, ADASA developed the Integrated Water Resources Management Plan of the Federal District - PGIRH (ADASA, 2012), a regional plan establishing both general and specific guidelines for water management in the capital. The plan implemented a model in which the region was divided into 40 units of analysis (Hydrographic Units), or micro basins, where reference flows, the Qmmm (average of the monthly minimums), were calculated for each. Through this instrument, it was established that the sum of all grants given for a hydrographic unit will be limited to 80% of its Qmmm, thus maintaining remaining flow corresponding to 20% of the reference flow (Distrito Federal, August 15, 2017).

This rule applies to all water bodies within the domain of the district. The maximum value for the granting of water abstraction, when in reservoirs, is defined based on the regularization flow of the reservoir basin, having a limit of 90% of the reference flow for funding human supply, and 80% for other funding (Distrito Federal, August 15, 2017). In general, studies for concession of the use of water resources are carried out with the understanding that statistical analysis of historical data will serve as basis for management. A new Water Resources Plan (Plano de Recursos Hídricos das Bacias Hidrográficas dos Afluentes distritais do Rio Paranaíba – PRH/Paranaíba) was released in 2019 where the most important water supply basins were evaluated. This plan verified water diagnosis and simulated prognosis related to water supply identifying scarcity scenarios where FD is prominent dependent on new water sources in order to avoid a future water crisis (ADASA & Engeplus, 2020).

2.2. System, Model, and Simulation

The need for water resource management presents several challenges for decision-makers, one of which is understanding of hydrological phenomena, which can be improved by environmental systems and equated through mathematical models. However, for compatibility and adequate comprehension of this theoretical framework, it is necessary to address some relevant concepts, such as system, model, and simulation, as Tucci (2005) pointed out in his work on hydrological models. This is because, frequently, the pragmatic processes of those responsible for water resource management systems are not satisfactorily conceptualized or do not meet the requirements for scientific research. It is noteworthy that there is no universal vision for these terms (Christofoletti, 1999), hence the need to contextualize the themes from the perspective of water resources.

One concept of a system was brought up by Tucci (2005) and Dooge (1973), in which the second pointed out that after consideration of a series of definitions, he proposed in general terms, and presented here in brief, that a system is a structure that correlates inputs and outputs in a given time reference. The author understands that the hydrological cycle is a system, in which water transits or is stored throughout its phases, and this flow can be represented through subsystems such as evaporation, precipitation, superficial flow etc. Abbott & Reffsgaard (1996) classified the hydrological cycle or parts of it as a natural system, and the hydrological model is its representation.

Following this line, Dooge (1973) states that a model can be defined as a system capable of reproducing some, but not all, properties of a prototype. This concept was summarized by Tucci (2005), in which the model is a representation of a system. Dooge (1973) exemplified the model with the schematic representation of inputs and outputs of the relationship between rain, evaporation, infiltration, etc, in other words, mathematical understanding of the elements of the hydrological cycle. Aditionally, Abbott & Reffsgaard (1996) described it as a hydrological model determination based on the time-varying description of the natural system.

With respect to simulation, Dooge (1973) believed that it is a work of analogies, and Tucci (2005) added that simulation is nothing more than the process of using the model**.** With the aggregation of these concepts, it is interesting to consider Ford's position (1999) on mathematical models, in which they are built to capture key interrelationships within the system and, currently, due to new technologies, have been transformed into space-time computational models, streamlining use of time.

2.3. **Decision Support System**

In 1997, the World Meteorological Organization (WMO) published a series of documents analyzing the world’s freshwater resources. Estimates suggested that by the year 2025 two-thirds of the world’s population would be suffering from water stress (WMO, 1997) with the most severe consequences in developing countries as urban occupation surpasses that of developed countries coupled with the fact that these regions lack necessary infrastructure to meet that demand (Kjellén and McGranahan, 1997). Padowski and Gorelick (2014) demonstrated that 31 cities with more than 750,000 inhabitants will reach water vulnerability by 2040, which means that there is urgent need for better management of these resources.

Historical requirements of multiple purposes concerning water resources, especially to prevent water scarcity led to construction of dams, aqueducts, pipelines, and other structural engineering projects, beginning in ancient times and greatly expanding throughout the 20th-century (Biemans et al., 2011; Gleick, 2003). The allocation of water demand and storage required development of complex management systems demanding implementation of mathematical models. (Porto *et al.* 2003). In general, these models were created to improve understanding of the environment's behavior as well as to control it (Hipel, 1993), however, models usually present some uncertainties (Beven and Freer, 2001). To counteract the intrinsic deviance and enhance the model's performance, optimization of simulation models was attempted (Loucks, 1993), such as the Decision Support Systems (DSSs) developed especially to asseverate representation of a model and allow for its operation (Loucks and Van Beek, 2017).

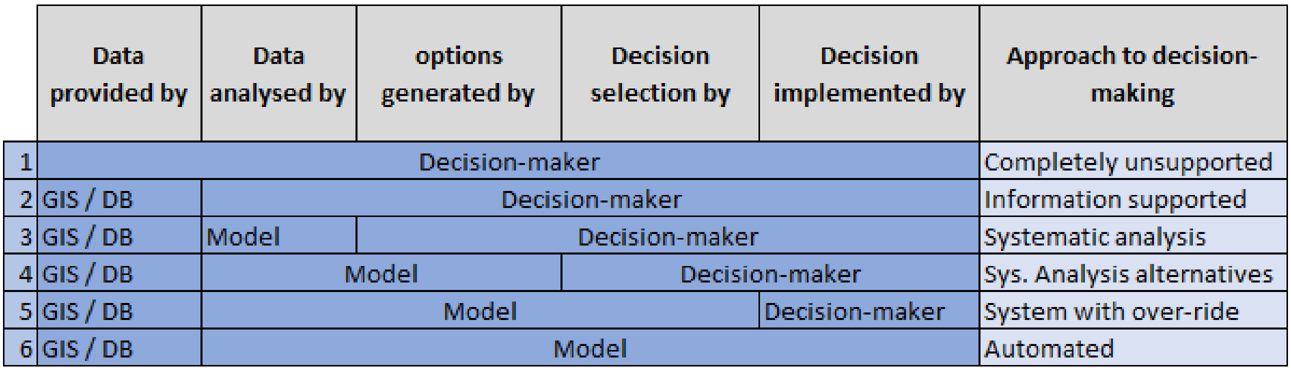
DSSs are inserted into the system concept proposed by Dooge (1973). DSSs have been discussed since the 1960s across diverse scientific areas, including water resources (Mass et al., 1962), primarily as a result of rapid population growth in urban centers and the consequent need for hydropower and stable water supply (Fredericks and Labadie, 1995; Labadie, 1993; Rocha et al., 2015).

Labadie and Sullivan (1986) recognized a common question understood in those decades which can be synthesized in how the management and operation of complex water systems can be improved, especially due to the unstable and, often, confusing field of Information Technology (IT). As emphasized by Fick and Sprague (1980) during that time, the need to improve efficiency and effectiveness of organizations initiated a search for IT solutions. Despite the complexity of challenges sounded by water resources managers some experiments related to DSSs started to appear (Fick and Sprague, 1980). Sprague (1980) organized the concepts that existed at that time into essential features related to a general DSS: a focus on underlying problems, the use of models with data access and retrieval functions, ease of use for people not computer savvy, and flexibility to adapt to changes. The author also suggests that the main point of DSS is improving the performance of decision-makers. From a water resources perspective, Yeh (1985) demonstrated that the key points for DSSs concerning reservoirs were development and adoption of optimization techniques for planning, design, and management. Fredericks and Labadie (1995) added that DSSs should maintain two function groups: database/model base management, and dialog/interface management. Turban et al. (2007) defined DSS application as a methodology for supporting decision-making to solve complex problems, with an interactive, flexible, and adaptable computer-based information system. Finally, Loucks and van Beek (2017) summarized the DSSs in two key points: a friendly interface, where manipulation, understanding, and visualization of the data is easy; possibility to control operations of the model.

DSSs can play a significant role as a support tool for generating future scenarios (Ahmadi et al., 2020) and in reducing the model's uncertainties (Su et al., 2020). This process is an important functionality for decision-makers that provides reliable information about trends related to water resources based on changes in climate, land use, and water demand, for example (Dong et al., 2013). Based on expected water scarcity scenarios (Padowski and Gorelick, 2014; Vörösmartry et al., 2000) and the necessity for comprehension of models and water demands, DSSs were created and have been improved upon over the years (Qian et al., 2011; Teodosiu et al., 2009).

Because water resource management is specific to each country/region, a particularity of DSSs are their relationships to local characteristics, based on elements such as culture, geography, history, and economy (Jonch-Clausen, 2004). This condition advanced development of many DSSs around the globe (Qian et al., 2011; Teodosiu et al., 2009). Different models used in DSSs have been developed and implemented, based on various regional criteria (Devia et al., 2015; Tomlinson et al., 2020). Hence, the development of a DSS supported by local data, using a well-known model that has proven reliable in the study area is fundamental (Mohammed et al., 2018; NASEM, 2018; Qi et al., 2018).

In general, as pointed out by Beven (2007), as technologies change, models and their use should change as well. Thus, with regard to proper management, Loucks and van Beek (2005) detailed in Figure 2-2 that computational models can perform several functions in a decision-making system, either as simply a data generator or through automatic decision-making, as is the case, cited by the authors, of the automatic closing of floodgates in the port of Rotterdam. The authors point out that an essential element of the system is the interactive interface, where both the entry and the display of data, as well as the control of model operations, are permitted in an easy and meaningful way.



	Data provided by	Data analysed by	options generated by	Decision selection by	Decision implemented by	Approach to decision-making
1	Decision-maker					Completely unsupported
2	GIS / DB	Decision-maker				Information supported
3	GIS / DB	Model	Decision-maker			Systematic analysis
4	GIS / DB	Model		Decision-maker		Sys. Analysis alternatives
5	GIS / DB	Model			Decision-maker	System with over-ride
6	GIS / DB	Model				Automated

Figure 2-2: Phases of the Decision Support System. Adapted from Loucks et al. (2005).

2.4. **Hydric Balance**

One of the main bases for the development of hydrological models is the calculation of the water balance, or the relationship between all water inputs and outputs in a given environment, in which the sum of all inputs tends to be equal to all outputs (Brutsaert, 2005; Hooper, 2005). This principle has been used since the 1940s (Thornthwaite, 1948) and has undergone several revisions over time (Xu and Singh, 1998). The general formula for the calculation is given by equation 1 (Oke, 1987):

$$p = E + \Delta r + \Delta S \qquad (1)$$

Where: p is precipitation, E evaporation, Δr variation change in runoff and ΔS represent changes in the volume of a reservoir, which for the proposed case would be soil moisture.

Brutsaert (2005) provides an adaptation for reservoirs given by equation 2:

$$E = P + [(Q_{ri} + Q_{gi}) - (Q_{ro} + Q_{go})] - \frac{dS}{dt} \qquad (2)$$

Where: E is the average rate of evapotranspiration in an area, P is the average rate of precipitation, Qri and Qro are total inflows and outflows from the surface of the river systems, Qro and Qgo correspond to total inflows and groundwater exits, per unit area, and finally dS/dt corresponds to variation of water volume in the environment.

Each variable that makes up the water balance therefore, represents, in itself, hydrological phenomena, and for these, several works have been done to understand each of these phases in isolation (subsystems). As an example, we can mention: the recharge of aquifers (Naik et al., 2008); soil infiltration rates (Assouline, 2013); pluviometry (Ahrens, 2009); and evapotranspiration (Douglas et al., 2009).

Another important approach is the study of the phases of the hydrological cycle in a given area, such as those been done previously in the Federal District and surrounding areas: Hydrogeology (Campos, 2004; Fiori et al., 2010; Silva and Kato, 1998); Pluviometry (Alves et al., 2015; Baptista, 1998; Borges et al., 2016), and Evapotranspiration (L. F. C. de Oliveira et al., 2001).

This can be further subdivided according to use of the territory, such as urban and rural for example. In relation to urban environments, the works of Grimmond et al. (1986), Cleugh et al. (2005), Mitchell et al. (2003), and Mitchell et al. (2007), sought to understand dynamics promoted in the means of water circulation by human action, adding new elements to the hydric balance such as water collected for human supply, sewage and storm drainage.

2.5. **Computational Hydrological Models**

The use of algorithms for modeling of water resources can be observed since the 1960’s. In parallel with the evolution of computers, these applications have improved in terms of performance and solutions (space-time for example), including with regard to the possibility of control through graphical interface (Arnold et al., 1998). Thus, there is a wide variety of computational models used in the area of water resources, as pointed out by Loucks et al. (2005). Several authors have reviewed these studies (Abbott & Refsgaard, 1996; Becker & Serban, 1990; Devia et al., 2015; Fatichi et al., 2016; Singh & Frevert, 2006; Sood & Smakhtin, 2015; WMO, 2009) and here we will focus on the model that will be used in this current research, the SWAT.

2.6. **SWAT**

The SWAT is a hydrological model, developed for semi-distributed modeling with a temporal analysis scale that can be used alone, or with a graphical interface in GIS (ArcGis or Qgis). It has the capacity to model hydrosedimentological data, pesticides, and nutrients. SWAT seeks to model subsystems of the hydrological cycle such as evapotranspiration, surface runoff, baseflow, infiltration, etc. (Sophocleous et al., 1999; Srinivasan et al., 1998). Its development began in the 1980s (Arnold et al., 1998) and has been continually improved upon until today (Version 681 of June 2020). It has proven effective and has been widely used in several areas of hydrology, both quantitatively and qualitatively, with a multitude of published works (Douglas-Mankin et al., 2010; Gassman et al., 2014; Tuppad et al., 2011). There are also some reviews in the literature regarding the state of the art of this model, as well as its development, such as the works of Gassman et al. (2007) and Bressiani et al. (2015). Besides the cited elements, SWAT was chosen to be used in this research because some reasons: it is considered a robust model with several satisfactory results, it is widely used in many parts of the world, it is possible to find large documentation, and it is free and open-source (Arnold et al., 1998; Bressiani et al. (2015); Douglas-Mankin et al., 2010; Gassman et al., 2014; Tuppad et al., 2011).

Regarding use of SWAT in Brazil, the first date from 1999, however, its application in a more effective way has only occurred recently. (Bressiani et al., 2015). The broadest review on the use of SWAT in the country was done by Bressiani et al. (2015), in which 102 publications were verified, between 1999 and 2014. The authors found most studies were aimed at testing the possibility of using SWAT for specific Brazilian basins and evaluating results according to different land-use scenarios. Another interesting survey observed in the research concerns the focus of the studies, in which the majority (48%) were concerned with the flow of rivers, and a large percentage (36%) were also concerned with sediment transport. With respect to the years following this review, 2014-2018, it was verified, using the research tool for scientific works using the SWAT - Swat Literature Database for peer-reviewed Journal Articles, that 63 works were published (in English and Portuguese) and applied in Brazil. This number outlines the relevance of this type of model for hydrological studies in the country.

Regarding the application of SWAT in the Federal District, it is possible to find dissertations, theses, and articles that developed projects in the region, which will be presented as hydrographic basins, due to the number of studies.

In the Rio Descoberto basin, an important water resource in the region, the works of Ferrigo et al. (2011) and Ferrigo et al. (2014) focused on production of sediments in the basin, taking into account different land uses. In the same basin, Ferrigo et al. (2015) applied SWAT to calculate water balance. In the Ribeirão Jardim basin, a study by Castro et al. (2016) sought to verify suitability of a small series of data (2 years worth) for use of the model in the basin, identifying the need for a larger study, mainly due to the necessity of more data for the validation process.

In the Paranoá basin, works applied in the Riacho Fundo sub-basin can be found in the literature, as proposed by Ferreira et al. (2017), who performed hydrological modeling there, performing a sensitivity analysis on the *alpha_bf* parameter. In the Gama sub-basin, hydrological modeling was carried out by Ferreira and Uagoda (2016), which focused on analyzing the prediction of water balance in the basin. In the Santa Maria sub-basin, Strauch & Volk (2013) performed hydrological modeling focused on the growth process of native vegetation in the cerrado. Nunes et al. (2020) used SWAT to model the entire Paranoá basin, and also determined the water balance of Lake Paranoá.

In the Ribeirão Pipiripau basin, studies have been carried out, such as those by Strauch et al. (2012) testing the impact of rainfall data from different sources for analysis of uncertainty in the flow simulation in SWAT; Strauch et al. (2013) verified impact of best management practices on the flow simulation and, finally, Salles et al. (2015) who compared two results using two different soil bases as input.

With regard to the database, it should be noted that although SWAT comes with a database, it was designed to be used for the soil and vegetation of the USA (Arnold et al., 1998). Brazil, being a large country with a wide variety of soil classes and many different types of natural vegetation (Bressiani et al., 2015), requires creation of specific databases for each region of the country, as demonstrated by Salles et al. (2015) and Baldissera (2005). Therefore, it is necessary to insert new soil and vegetation classes or to adapt existing values in relation to the study area (Salles et al. 2015).

In recent years, different assessments have been done in the Federal District, and a local database has been developed by Lima et al. (2013). They proposed a soil database using information collected from 56 sampling points in a sub-basin at the head of the Rio Jardim basin, further tested later by Salles et al. (2015) in the Pipiripau Basin, which yielded better results than when using the database built by Baldissera (2005), which was created for the Cuiabá River in Mato Grosso. Ferrigo (2014) in turn applied the database proposed by Lima et al. (2013) to the Descoberto River Basin, where he also obtained good results. However, the development of this database was based on samples collected in a small hydrographic basin of 104.86 km², which may not adequately represent the variety of soils that make up the Federal District (GDF and SEMA, 2012).

Despite improvements observed in the results of these surveys, when values of the parameters were verified, such as saturated hydraulic conductivity or depth of the soil surface at the bottom (per layer), it is perceivable that these values present great variability for several different points within the FD. For example, Saturated Hydraulic Conductivity in Yellow Red Latosol was described by Lima et al. (2013) with an average value of 1112.85 mm/hr, whereas Fiore et al., (2010) verified an average of 90.414 mm/hr. That said, the need for data from more diverse samples throughout the capital is important, for creation of a range (range) of physically acceptable values to be used in calibration steps of the hydrological model.

Another interesting point in the SWAT, identified by Strauch & Volk (2013), was behavior of the plant cycle, in which they focused on understanding the process of estimating the leaf area index (*Leaf Area Index*). They noted that plant growth processes in the Federal District are not started by heat or on a specific date, as suggested in the SWAT manual (Neitsch et al., 2011), but are directly related to the beginning of the rainy season starting between September and November. Consequently, Strauch & Volk (2013) created a modification to the SWAT source code to deal with this situation. With respect to the database, the authors used the original for SWAT, with adaptations for soils and vegetation.

Despite broad application of SWAT for hydrological modeling, with respect to groundwater, the model presents some difficulties. Nguyen & Dietrich (2018) pointed out that two of the greatest limitations are related to the non-spatial reference of the HRU (Hydrologic Response Unit) concept and a simplified concept of groundwater. These conceptions contribute to the low performance in the simulation of base flow and its inability to simulate regional groundwater. Nam et al. (2008) stated that due to the fact that the model is semi-distributed, its groundwater component does not consider, parameters such as hydraulic conductivity and storage coefficient, as being distributed, and also equally difficult to calculate water distribution at the head and abstraction rates, explaining this difficulty.

2.6.1. SWAT Theory

The SWAT model gathers a series of modules, each responsible for particular processes related to water quantity or quality. The hydrologic model in SWAT can be synthesized according to Equation 1:

$$SW_t = SW_0 + \sum_{t=1}^{t}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \qquad (1)$$

Where SW_t is the final amount of soil water (mm H_2O), SW_0 is the initial soil water (mm H_2O), *t* is the time (days), R_{day} represents the amount of precipitation on the day *i* (mm H_2O), Q_{surf} signifies the amount of surface runoff on day *i* (mm H_2O), E_a is the amount of evapotranspiration on day i (mm H_2O), w_{seep} is the amount of percolation water exiting from the soil profile bottom on day *i* and Q_{gw} is the amount of water flowing to the rivers on day *i* (mm H_2O) (Neitsch et al., 2011).

To estimate hydrological flow, the SWAT model requires five datasets as climatological input data: temperature, air humidity, wind velocity, solar radiation, and rainfall. The first four datasets are used to assess evapotranspiration with the Penman-Montieth equation, and the last one is used as the main force in the model. SWAT is based on daily steps and for each day the elements for Equation 1 are assessed based on the processes described in Figure 2-3.

On day *i* for each HRU, the SWAT model assess the elements of Equation 1 following the order described in Figure 2-3, i.e., updates the CN (curve number) for each HRU; estimates the amount of water released in the runoff process if precipitation is larger than 0.1; estimates the infiltration; estimates lateral streamflow if infiltration is higher than Field Capacity; estimates evapotranspiration, percolation, and baseflow. This process representing the land phase in the SWAT model is depicted in Figure 2-4. The water coming from rain moves through the different reservoirs in the SWAT conception. Main water flows used to generate streamflows come from runoff, subsurface flow (lateral flow), and baseflow. Infiltration, percolation, and recharge are vertical fluxes that regulate the quantity of water available for those flows.

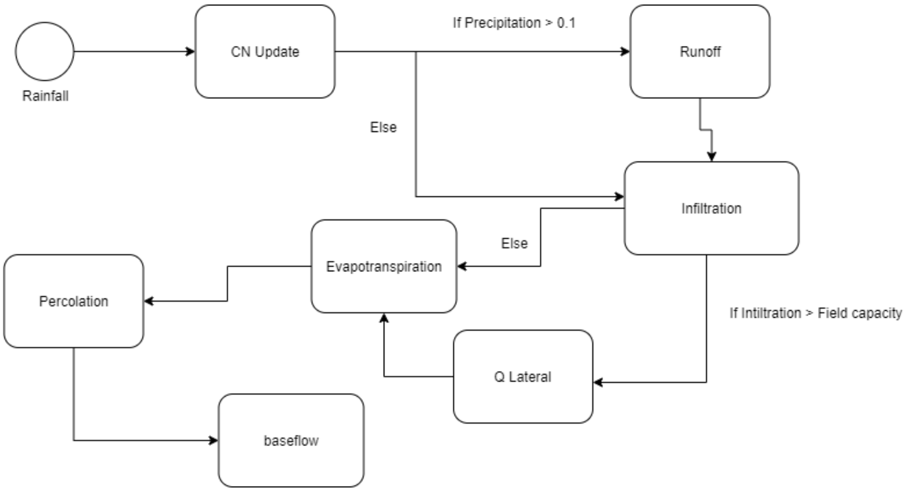


Figure 2-3: Hydrological flux in the SWAT

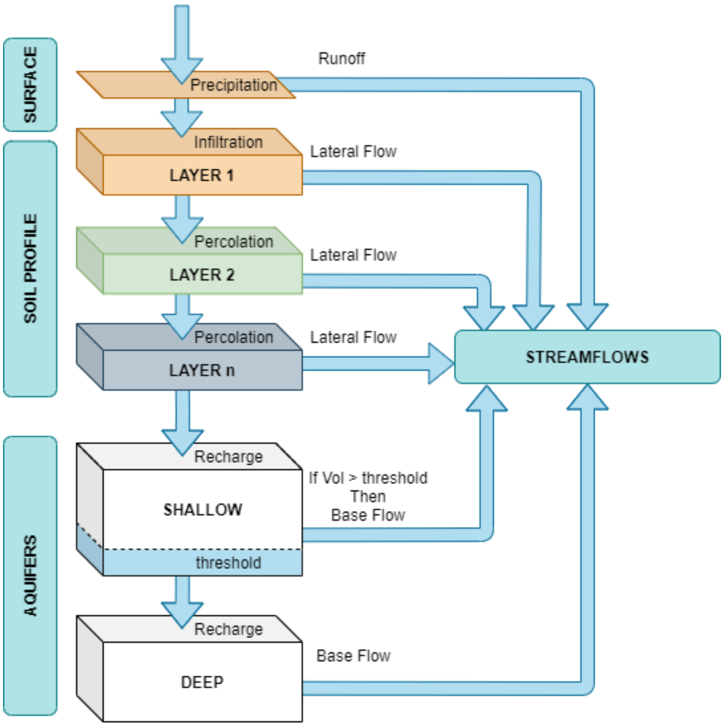


Figure 2-4. Representation of the land phase in the SWAT Model

Additionally, comprehension of the water flux's order is essential to understand the model, especially when there is a need to alter any internal functionality in the SWAT. Therefore, identification of all individual process codes within the source code is important. Figure 2-5 describes the most important codes executed daily for every HRU during the simulation.

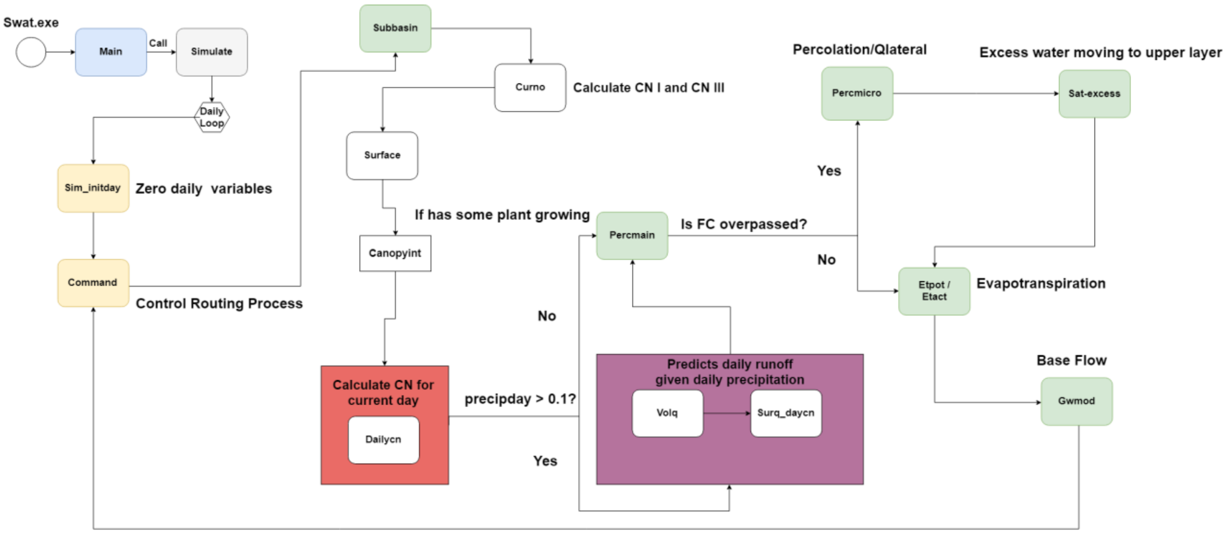


Figure 2-5: Codes responsible for each process in the SWAT model

Understanding the flux depicted in Figure 2-5 is the key to proposing any changes to the SWAT default model. Each box in Figure 2-5 represents a different process in the source code. The SWAT structure was built to allow, in general, one code for each process and/or sub-process which has been given in Equation 1. Each code will be described following the arrows: Swat.exe is the SWAT model executable; Main is the code responsible to guide the model; Simulate starts the daily loop for the hydrologic processes; Sim_initday zeros all daily variables; Command controls the routing process; Subbasin is responsible to start basin process; Curno calculates CN I and CN II; Surface control the process over the surface; Canopyint computes canopy interception of rainfall; Dailycn calculates CN value for current day; if the amount of precipitation is greater than 0.1 in the current day, Volq and Surq_daycn will assess Runoff; Percmain verifies if Field Capacity is exceeded; Percmicro and Sat_excess estimate Percolation and Lateral Flow; Etpot and Etact assess potential and actual evapotranspiration; the last process is Gwmod which is responsible for estimating groundwater recharge and baseflow. The proposed study in this thesis made changes to two codes, seeking improvement in three processes: runoff, recharge, and baseflow. The modifications will be detailed in chapter 7.

2.7. Federal District and its sources

The Federal District - FD - (Figure 2-6), the chosen study area, is located in the central midwest region of the country delimited by parallels 15 ° 30 ' S and 16º 03 'S, having, on the east, the Rio Preto and, on the west, the Rio Descoberto. The three main sources for human water supply are Lago Descoberto, Lago Santa Maria and Lago Paranoá, as seen in Figure 3 7.

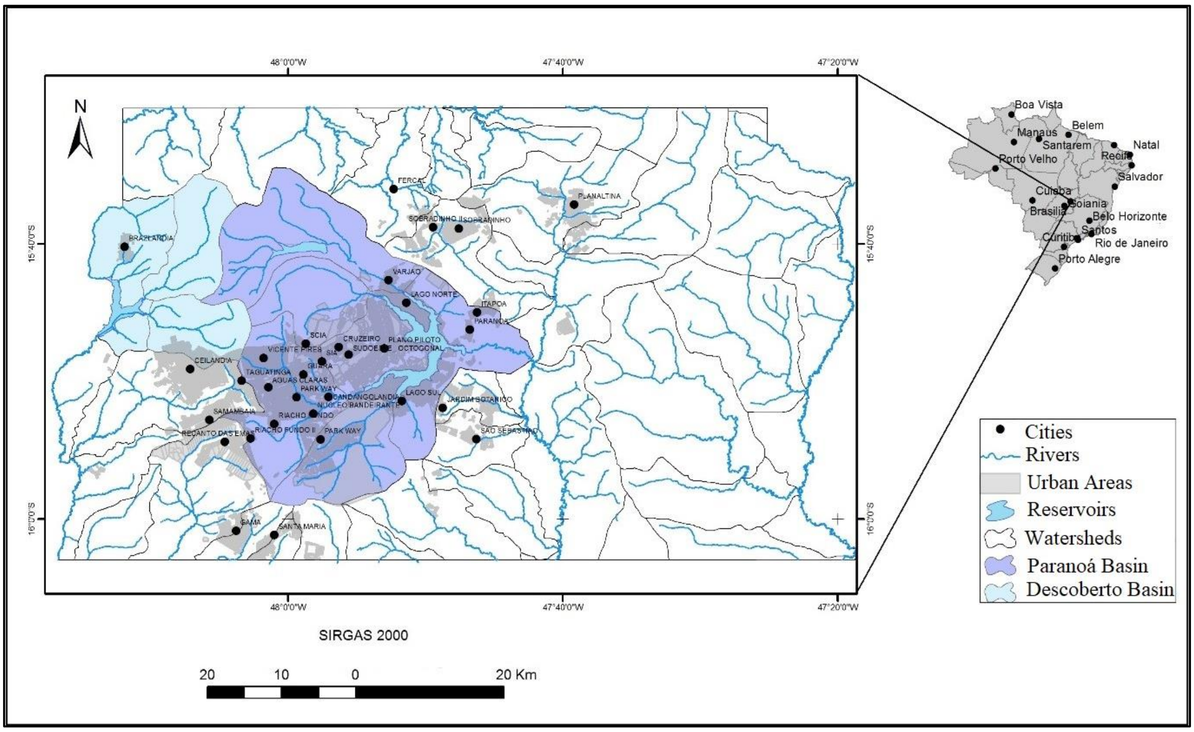


Figure 2-6. Federal District with focus on basins used for human supply

The region is a focal point of the urban expansion process, as can be seen by its central area, delimited by the Lago Paranoá Basin (Menezes et al., 2010), containing the reservoir that gives name to the basin, was used for human supply due to the 2018 water crisis. It is surrounded by urban areas. In turn, the Santa Maria reservoir is positioned within a permanent environmental protection area, the National Park of Brasilia (BRASIL, 2000), but it is at risk of suffering from human action, due to the occupation and soil use in its buffer zone, a phenomenon shown by Menezes et al. (2010). This anthropic process can also be observed in the Rio Descoberto Basin, where the reservoir of the same name is located and whose primary function is human supply, although it occurs on a smaller scale. An important observation regarding the relevance of these last two reservoirs (Santa Maria and Descoberto), stems from the fact that, together, both supply 82% of the population of FD (GDF, 2017)

Lake Paranoá has become a reservoir of multiple interests, mainly due to its geographical and urban positioning, transforming it into a landscape, and leisure landmark. Its geographical position brings with it fragility regarding quality and quantity of water due to the intense occupation of the margins and their contributing basins. Studies at the turn of the century (Felizola et al., 2001; Unesco Brasil, 2002) determined that, between 1954 and 1999, approximately 41% of the vegetation cover of its lake contribution basin disappeared. Studies carried out by the team for this project, especially Menezes (2010) and Menezes et al. (2010), updated use and occupation data for 2009 and found the lake is subjected to high, constant anthropic pressure, not only due to degradation of the tributaries' hydrographic basins but also as a result of countless activities concentrated at its margins, which have invaded the water mirror area, directly impacting useful volume. The growing urban expansion can be seen in Figure 2-7, which shows growth of the urban area from 1973 to 2009.

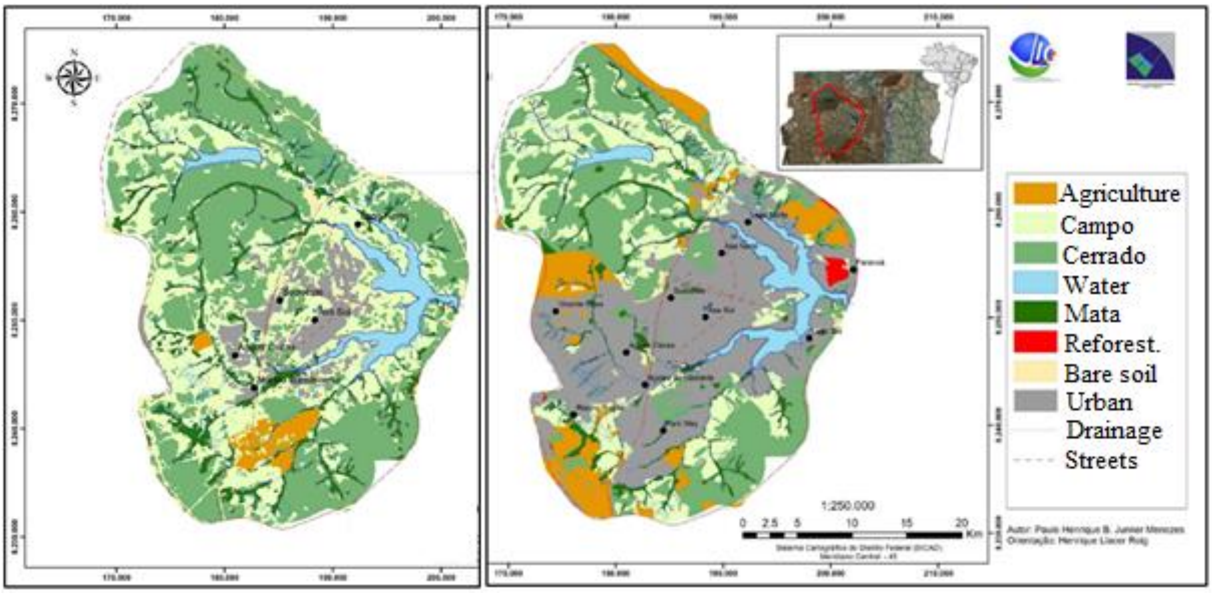


Figure 2-7. Land use and occupation in 1973 and 2009. Source: Adapted from Menezes (2010).

There has also been in recent literature, studies that analyzed important points related to the hydrological process of the region. Regarding anthropic influence in the study region, we cite the work of Dias & Walde (2013), who analyzed changes in land use and occupation over the years, Penna (2002), who dealt with the disorderly growth of the region, and Menezes et al. (2010) that correlated these advances with impacts on runoff and detection of changes and evolution of the environment.

The Lago Paranoá Basin, the conservation unit in which the Santa Maria reservoir is located, deserves attention, given that in addition to the factors mentioned in terms of urban expansion in the basin, there is the presence of an uncontrolled landfill. Some studies have assessed the contamination plume present in the region and have even identified presence of structural flaws (Pereira et al., 1997), which can accelerate the contamination process. Evidence of contamination was further suggested by Campos et al (2014), who analyzed data from a monitoring well near the landfill, in which high values of conductivity and chloride were observed, indicative of contamination.

The Descoberto River Basin has been the subject of articles and theses over the last few years, mainly due to various conflicts of land use (Nunes and Roig, 2016) and human supply (GDF, 2017). Some works focused on carrying sediments (eg BICALHO, 2006), others soil characterization (eg Reatto et al., 2003), and still others on modeling and management of water resources (e.g. Ferrigo, 2014; Ferrigo et al., 2015; F. da S. D. Oliveira et al., 2014). It is noteworthy that in addition to urban expansion processes in the FD, this basin must be compatible with agriculture, which represents an important economic driver for the region (Chaves et al., 2010; Mello, 2009).

The Corumbá reservoir, despite not belonging to the Federal District, should also be considered in any analysis of capital management, since it is used for shared supply of the Federation Unit and some cities in the vicinity belonging to the State of Goiás (GDF, 2017). The reservoir also contains an HPP (Hydro Power Plant), Corumbá IV (CORUMBÁ CONCESSÕES, 2018) and is surrounded by cities whose expansion is an influence, in addition to some tributaries already receiving effluents (Nóbrega, 2005), which may present future problems.

The present study verified the delicate situation in the Federal District regarding its water availability, reinforcing the need for more efficient management, especially in the wake of crises experienced in recent years (2017/2018). A more detailed analysis of the availability of water resources for the year 2018, furthering that already described in the introduction, revealed a situation of extreme scarcity when compared to the parameter of 1,700 m³ per inhabitant used by UNP (UNDP, 2006). Taking the volume of the two main reservoirs on January 1, 2018 (Descoberto: 22 hm³ and Sta Maria: 18.69), and adding flows estimated by ADASA for the current year (ADASA Resolutions nº 08 and 12, both of 2018), a volume of 195 hm³ was presented, which would represent the total amount of water available for the entire period. This value results in 65 m³ per inhabitant, and represents a major shortfall compared to values used by UNDP. With this understanding, an integrative, efficient support system can be a critical tool for strategic planning in the region. Also, existence of measured data is fundamental to this process since this information is the most important element in water modeling. Accurate modeling depends on precise data and long history series (for most studies is recommended more than 30 years) in order to get variations through the analyzed period and produce confident results.

2.8. **References**

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3. MATERIALS AND METHODS

3.1 Area of Study

The Federal District - FD - is located in the central midwest region of the country and is Brazil’s Capital. The district is placed in highlands and most of the area counts with heights higher than 1000 meters above the sea (Figure 3-1). Also, there are springs of three major Brazilian hydrographic basins: Tocantins-Araguaia (to the north), São Francisco (to the east), and Paraná (west, center, and south).

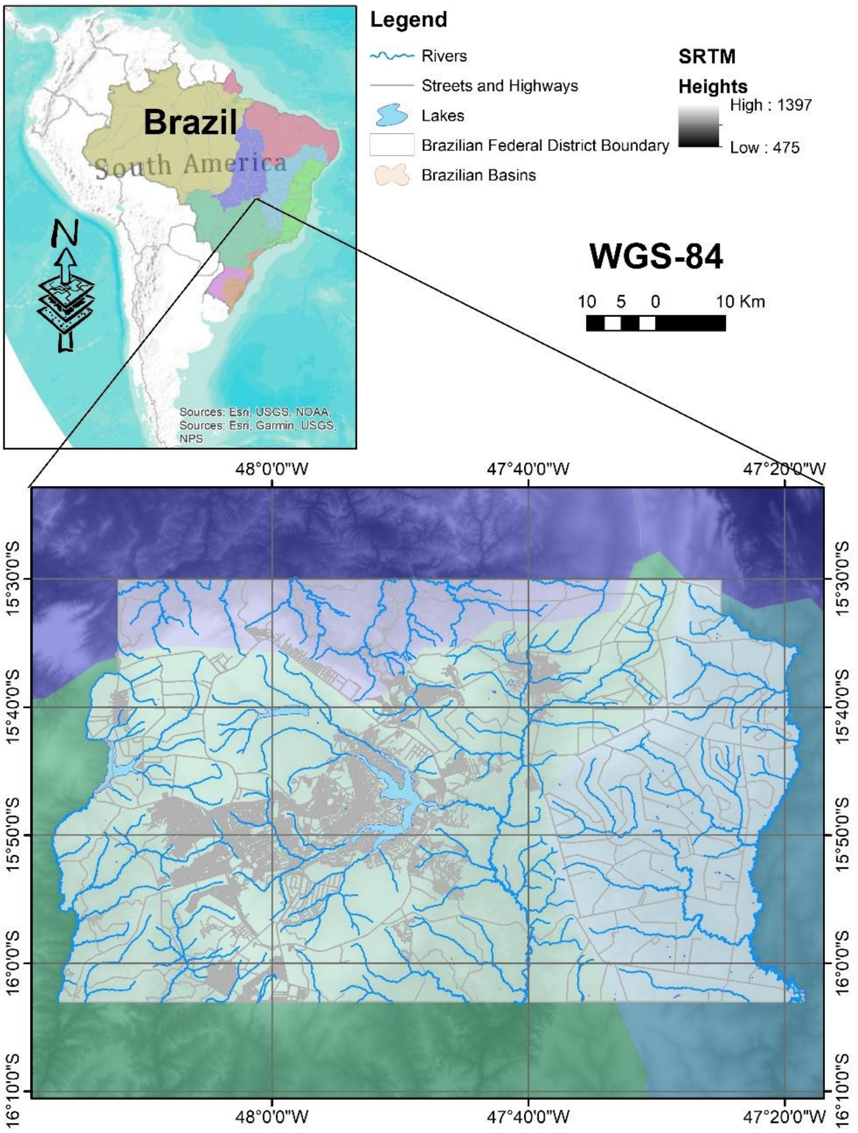

Figure 3-1. Study area location, in the middle of Brazil and South America

The FD geology characterization can be found in Campos and Freitas-Silva (1998), where they describe the stratigraphic column of the district as composed of 4 groups: Canastra, Paranoá, Araxá, and Bambuí. The Paranoá Group covers an area of 65% of the FD and is formed by Sandy Metarrithmite, Medium Quartzite, Clay Metarrithmite, and Psamo-Pellitic-Carbonate (GDF & SEMA, 2012; Gonçalves et al., 2015). The Canastra and Bambuí groups each occupy 15%, the first of which occurs on the southern border of the São Bartolomeu river valley, consisting basically of phyllites and lenticular bodies of marbles and quartzites; the second, on the other hand, takes place on the eastern border of the Federal District, formed by siltstone, shale, and arkoses. Finally, the Araxá Group is identified in the southwestern part of the district, occupying about 5% of the territory of UF and being formed by schist and quartzite lens covered by a thin layer of soil in the majority of the area (ZEE, 2009; Campos and Freitas-Silva, 1998). Also, most of the soils can be described as oxisols (Gonçalves et al., 2015; Lima et al., 2013).

The climate of the Federal District is characterized by two well-defined seasons: a hot and rainy period extending from October to April and another period of cold, dry weather lasting from May to September (Baptista, 1998; Helen Camargo Costa et al., 2012). The period from September to April is dominated by concentrated rains the majority of which occur in the DEC-JAN-FEB quarter. Between April and August, there is almost no precipitation with low air humidity, reaching levels around 10 % and, periods of more than 120 consecutive days of drought are not uncommon (Baptista, 1998; Campos, 2004). In analyzing pluviometry data from 1978 to 2008, Costa et al. (2012) pointed out that in the southern part of FD, rainfall values varied between 1500 mm to 1800 mm, and in the rest of the region variations from 1200 mm to 1500 mm were verified. Alves et al. (2017), analyzing a 16-year historical period (1998 to 2014), also found similar results with respect to spatial and temporal heterogeneity in the distribution of rainfall, having observed an average of 1430 mm for the studied period.

Regarding air temperatures, cold air masses of high southern latitudes affect the southern region in the winter, contributing to low temperatures and colder weather conditions, mainly in the southern part of the District. According to the Köppen classification, the predominant climatic type in the region is humid tropical - AW - which covers most of the region (GDF and SEMA, 2012). Also seen in the FD is a seasonal variation in temperature, where the annual average is 21.2 ° C’. The highest average temperatures are recorded between the months of September and March with June and July registering the lower average values. Average annual temperature is 21.2° C (GDF and SEMA, 2012).

The Federal District (FD) is a planned territory chosen as location of the Brazilian capital city, Brasília. It was created to shift governmental functions away from the more developed southern coast to lesser developed regions in the interior of the country (Stephenson, 1970). It was inaugurated in 1960, and planned for a maximum population size of 600,000 inhabitants (Madaleno, 1996). Today the FD has more than 3 million people (IBGE, 2020), living in a dynamic urban area alongside areas of agricultural production (Lorz et al., 2016), with 94% of the population living in urban areas (Lorz et al., 2012). And it expected 4 million people in 2040 (ADASA & Engeplus, 2020; IBGE, 2020). Freshwater comes from three reservoirs, responsible for 82% of the total water supply: Santa Maria, Descoberto, and Paranoá (Barcellos et al., 2018). The last was included as an emergency source in 2018 (Barcellos et al., 2018). The other 5% of the total water supply comes from groundwater (de Moraes et al., 2008), and the remaining demand is supplied directly by withdrawal from streams (Vasyukova et al., 2012).

The initial planning suggested population growth could affect life quality in the city (Madaleno, 1996), and future scenarios forecasted in 2010 suggested that the city would face problems concerning water availability (Aster et al., 2010). Also in 2010, according to the water supply company, water demand exceeded the system’s capabilities (Kalbus et al., 2012; Vasyukova et al., 2012). Additionally, some rivers have presented significant decreases in baseflow discharge (Lorz et al., 2012). This urgent situation, and subsequent three-year period from 2016 to 2018, where observed rainfall was equivalent to 75% of the historic average, led to crisis conditions in the Federal District (Lima et al., 2018). The government managed to control multiple-use water and ensure water security, prioritizing the human water supply (Barcellos et al., 2018; GDF, 2017).

3.2 Structuring the proposed system

Aimed at developing a water resource management system, the present study is based on the formulation of a DSS (Decision Support System) defined by 5 phases and organized according to model 4 by Loucks et al. (2005), "Alternatives to Systematic Analysis" (Figure 3 2). It is noteworthy that within this system, each phase generates a set of intermediate data that can be used in conjunction with the final model, and associated with proposed scenarios, to aid in the decision-making process.

The first Phase represents organization of data, being: pedology, geology, geomorphology, digital elevation modeling (and derivatives such as slope), land use and occupation pattern, vegetation cover, hydrographic network, water system networks water distribution and capture (rainwater network, sewage, and supply) and hydrological data (pluviometric, fluviometric, sedimentological and etc.). All of these information plans are cataloged and organized to build a geographic database in the Postgres-PostGIS environment (Hsu and Obe, 2012, 2011) allowing for grouping, redundancy analysis, topological consistency, and versioning as well as a transfer process (ETL - Extract, Transformation, and Load) for specific formats of the applications to be used in the project. This treatment together with good practices in data collection is relevant because data quality can assume an important role in water modeling, improving or worsen the modeling (Gan et al., 1997).

This database can be used directly for hydrological modeling in the integrated SWAT/SWAT Cup (Abbaspour et al., 2015a, 2017; Gassman et al., 2007) that constitutes Phase 2 of the process – Data analysis and model generation. Finally, data is produced for the generation of scenarios (Phase 3), which will be used by decision-makers in Phases 4 (Selection of Scenarios) and 5 (Implementation of decision making). Thus, in order to improve performance of each model and develop efficient management systems, an integrated flow is proposed as shown in Figure 3-2 exemplifying the system's organizational process.

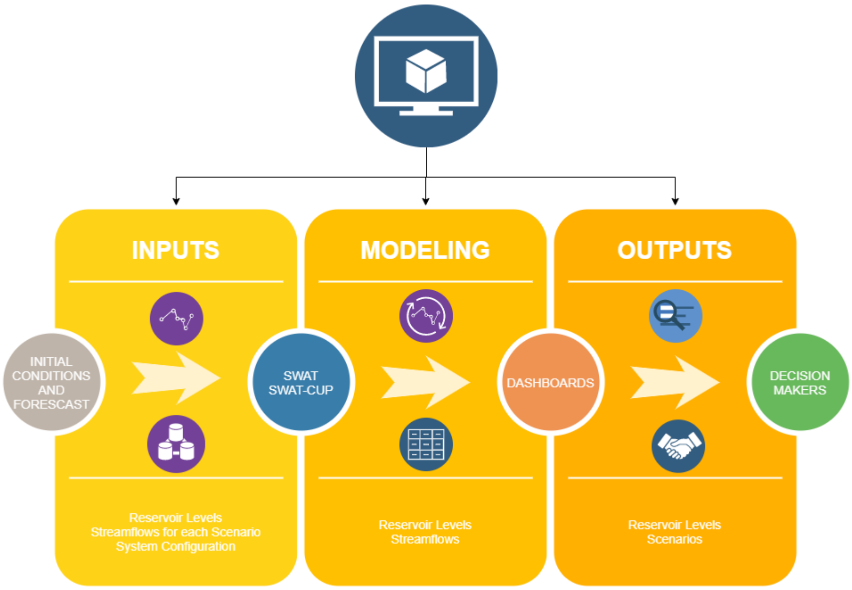

Figure 3-2 Decision Support System for Water Resources Management

3.3 The SWAT model and its database

Two keys elements are required for building a reliable water resource assessment: good hydrological data and a suitable modeling application (Abbott and Refsgaard, 1996). Once the model has been chosen, procurement of appropriate data for the specific application is necessary.

To update the SWAT database, and improve the model simulation, data was collected from various locations, utilizing existing works in the Integrated Development Region of the Federal District and Surroundings (RIDE / FD) with the purpose of creating a more realistic soil database.

The database proposed by Lima et al. (2013) was used as a reference. Works by Fiori et al. (2010) were used to improve the hydraulic conductivity database. Studies by Spera et al. (2005) and Maia et al. (2018) were used to improve data on soil density and available soil water capacity. The depth of the layers was changed to maintain consistency with the hydraulic conductivity tests performed and soil analyses by Fiori et al. (2010) and Spera et al. (2005) respectively.

For the database of parameters on vegetation cover, the work of Strauch and Volk (2013) in the Torto basin - FD was used as a reference given the satisfactory results obtained when comparing the simulated data of LAI and ET to the same extracted from MODIS sensor (collection 5 MOD15A2 and collection 5 MOD16A2, respectively).

For composition of the climatological database, the INMET-headquarters station was used for data on air humidity, temperature, radiation and wind speed, while rainfall data was taken from CAESB stations located in each basin of interest. Satellite data for possible coverage failures was also utilized.

For the simulation calibration, CAESB fluviometric stations distributed throughout reservoir basins were used, utilizing SWAT-CUP as an application for calibration. This application was developed to carry out automatic sensitivity analysis and calibration of SWAT data (Abbaspour, 2015). The land use map required in the model used was made by IBRAM in 2011 and was obtained from SEGETH's GeoPortal (State Secretariat for Territory and Housing Management). With respect to the digital elevation model required for the simulation, the Digital Terrain Model generated by the SRTM was used (Shuttle Radar Topography Mission).

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4. TRENDS IN RAINFALL IN THE FEDERAL DISTRICT

4.1. Introduction

Although Brazil is known for its substantial water availability, its spatial and temporal distribution is quite heterogeneous with very contrasting regions (WBCSD, 2005), as the semiarid in Northeastern Brazil and the Amazonian equatorial forest, both in the same latitudinal range. This situation is further complicated because population is not consistently distributed in relation to water distribution. In the Amazon basin, observed average flows to the order of 131,947 $m^3.s^{-1}$ can be observed and registers 8 million inhabitants, but there are also basins such as the East Atlantic with average flows of around 1,492 $m^3.s^{-1}$ and 14 million inhabitants. As a result, large urban centers in Brazil are already undergoing water crises (ANA, 2005).

The understanding of hydrometeorology phenomena has become increasingly important, especially that of precipitation, a key driver of the hydrological cycle (Pereira et al., 2018). Previous studies relate an increase in frequency and magnitude of extreme events in South America (Coelho et al. 2016; Oliveira et al., 2017; Cunha et al., 2018; Marengo et al., 2020), mostly related to the global warming trend. Identifying patterns in rainfall distribution over time is useful in planning (Paquin et al., 2016). Moreover, this identification seeks to minimize damage that may be caused by extreme, intense precipitation (Petineli and Radin, 2012) or drought (Mishra & Singh, 2010; WMO, 1997).

During the last decades, water crises have become more often in Brazil (Coelho et al., 2016; Nobre et al., 2016; Marengo et al., 2018; Panisset et al., 2018). The water crisis experienced in 2014 in the southeastern region of Brazil, namely the metropolitan region and most populous city in Brazil, São Paulo, was considered the worst since recording of measurements for reservoir systems began (Buckeridge and Ribeiro, 2018). Changes in precipitation regimes can be caused by several factors, including deforestation, urbanization, and emission of polluting gases into the atmosphere, along with intensification of solar activity and other natural phenomena (Marengo, 2010). Regardless of the causes of scarcity, whether by natural climatic variations or by anthropic interference, each unit of the federation (States) should monitor and verify the real situation of its water resources and their relations with border states. Continuous monitoring and consistent water management are critical for future planning (Loucks et al., 2005).

The chosen study area, Federal District - FD, contains headwaters of three important Brazilian hydrographic basins, the São Francisco River basin, the Tocantins basin, and the Paraná basin (ANA, 2005) which characterizes the region as made up of rivers and basins with low amounts of water flow (the mean annual streamflows vary from 3 m^3/s to 23 m^3/s) (Lima et al., 2018). Despite existing for just six decades, intense urban-population saturation has resulted in about 3 million current inhabitants being registered in FD (IBGE, 2020). The fast population growth and ensuing urbanization have generated a series of problems, such as illegal land grabbing (Penna, 2002), soil sealing (Menezes et al., 2010), overloading of basic public systems (transport, education, and health) (Ribeiro et al., 2015) and consequent environmental impacts (Dias and Walde, 2013; Franz et al., 2014).

From 2016 to 2018, the state experienced severe drought conditions (Lima et al., 2018). The usable water volume in the reservoirs fell to their minimum levels and a series of procedures to control the situation were implemented such as pipe control, water rotation among neighborhoods, and emergency withdrawals from new water sources, etc. (Lima et al., 2018). Aside from aforementioned issues, some studies pointed out that a large part of the scarcity had occurred due to reduction of rainfall in the region (Borges et al., 2016; Lorz et al., 2012). Hence, an analysis of rainfall data is fundamental for water management related to the FD.

The present study analyzed 21 rain gauges, looking at rainfall trends over time using four statistical methods: the Mann-Kendall test, Cox-Stuart, Wald-Wolfowitz, and Spearman. The results obtained are expected to support public policy for water resources resulting in more effective management of land use and occupation, as well as better understanding of water availability in FD. This type of analysis is important for decision-makers because identification of trends and/or stationary behavior is significant for planning and generation of future scenarios.

4.2. **Material and Methods**

In the following sections, the study area, as well as the statistical measures used in the paper will be described.

4.2.1. Study area

The Federal District (FD) is located in the central-west region of Brazil, within parallels 15° 30' S and 16º 03' S and has an area of 5,802 km². The main features of the regional climate are, alternately, dry and humid seasons. In spring and summer months, high humidity is associated with the Continental Equatorial (mEc), while in autumn and winter, dry weather prevails due to the advance of the Tropical Atlantic Mass. Regional climate is under the influence of the South American monsoon system (SAMS) and presents two well-defined seasons: a rainy and warm period from October to April, and dry and cold season from May to September (Baptista, 1998, Gan et al., 2004; Prado et al., 2021; Turner and Annamalai, 2012), where 45-55% of annual total precipitation occurs from December to February (Nimer, 1989; Alves et al., 2015), as it is observed in Figure 4-1. The annual mean total precipitation is ~1500 mm (Nimer, 1989; Baptista, 1998)

Precipitation in the DF region is mainly associated with the South Atlantic Convergence Zone (SACZ), but is also under the influence of local convection during warm and moisty summer days (Anunciação, da Rocha, et al., 2014; Anunciação, Walde, et al., 2014; Carvalho et al., 2004; Gan et al., 2004; Jose A. Marengo et al., 2012; Rodríguez-Zorro et al., 2020). During austral winter (June to August), the mean accumulated precipitation is below 30 mm.

The region is positioned at high altitude ranging from 750 to 1344 meters (Gonçalves et al., 2009). The eastern part of FD exhibits more rural activity, while the center and the southwest axis is mostly urban area with 94% of the population. The western part is where the two main reservoirs are situated, and together contribute 82% of the water for the local population (Lima et al., 2018; Lorz et al., 2012).

4.2.2. Rainfall Data

Rainfall data was retrieved from 21 rain gauges in the Federal District region (Figure 4-1). Rain gauges were chosen in order to have a minimum of 30 years in time series length, from January/1971 to December/2017. However, due to a missing data point or deactivation of some gauges, the studied period for the analyzed sites is not coincident (Appendix). The rainfall data was obtained from Companhia de Saneamento Ambiental do Distrito Federal (CAESB) and Instituto Nacional de Meteorologia (INMET).

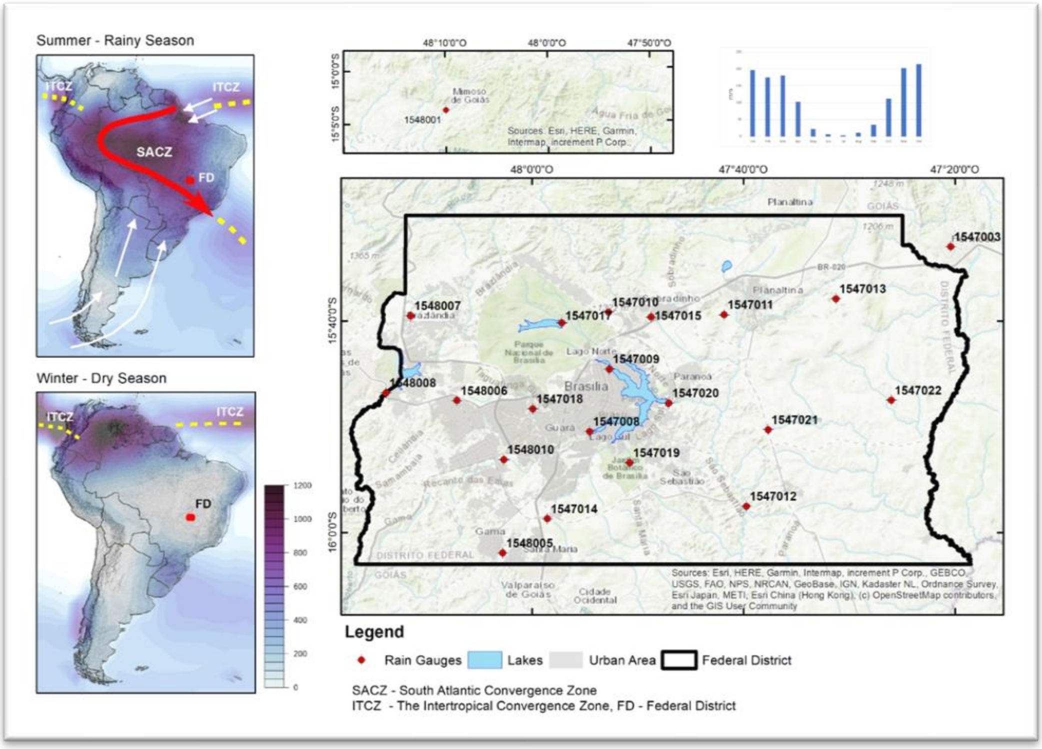


Figure 4-1- Rain Gauges distribution in the Federal District (Brazil), the study area, and climatological factors that influence the region as well as rainfall pattern over the year.

4.2.3. Statistical Evaluation

Rainfall trends were analyzed for water year, and by hydrological quarters (DJF, MAM, JJA, and SON). The latter was proposed to avoid seasonal variations (Hamed and Ramachandra Rao, 1998; Hirsch et al., 1982), using four non-parametric statistical tests in order to improve the analysis as suggested by Machiwal and Jha

(2008): Mann-Kendall, Cox-Stuart, Wald-Wolfowitz, and Spearman. Non-parametric tests are more suitable for natural time series because assumptions required for parametric testing are not usually present in this type of data (Hipel & McLeod, 1994; R. M. Hirsch & Slack, 1984). Rainfall data, for example, seldom follows normal distribution (Yue et al., 2002).

The Mann-Kendall test, hereafter referenced as **MK**, (Gilbert, 1987) is commonly used to check for trends in climatic conditions (WMO, 2009b). It is the most appropriate test to identify climatic change according to Goossens and Berger (1987) and is the most widely used test for trend identification (Yue et al., 2002). This test has been used by several studies in Brazil (Paiva and Clarke, 1995; Ribeiro et al., 2015; Sanches et al., 2013) and around the world (Bauwe et al., 2017; Hamed and Ramachandra Rao, 1998; Johannsen et al., 2016). As observed by Fatichi et al. (2009), studies using **MK** for trend identification tend to assume that sample data is independent. Although, as noted by Rao and Hamed (2019) and Fatichi et al. (2009), the correlation can significantly influence results. According to them, a positive correlation can increase the possibility of rejecting the null hypothesis, while a negative correlation acts to accept null hypothesis. Therefore, other trend tests were also used in order to improve our analysis.

The Cox-Stuart test, hereafter referenced as **CS**, (Cox and Stuart, 1955) is another test recommended to identify hydrologic changes (McCuen, 2003) and it was used to verify if rainfall datasets present variability and a monotonic tendency (Fatichi and Caporali, 2009; Jasim Hadi and Tombul, 2017). In addition, as suggested by Chen and Huang (2020), **CS** has the advantage of being independent of the data sequence structure, however, it is considered slightly weaker than Mann-Kendall (Rutkowska, 2015).

The **Wald-Wolfowitz test**, hereafter referenced as **WW**, (Wald and Wolfowitz, 1940) also known as a ***run test***, was applied to verify independence among the data series, as well as another perspective on trends in the rainfall dataset (Rao and Hamed, 2019; WMO, 2009b). This test has also been commonly used to examine trends in rainfall datasets (Haktanir and Citakoglu, 2014; Sharda and Das, 2005; Steinke et al., 2017).

The **Spearman's** correlation, hereafter referenced as **SP**, (Spearman, 1904) was the last test we used and is another recommended for trend analysis (WMO, 2009b). It is used to verify trends in rainfall datasets (Fatichi and Caporali, 2009; Ogallo, 1979; Tabari et al., 2012) and is recommended for environmental engineering applications (Hipel and McLeod, 1994). All four tests have also been used to verify trends in January rainfall data in FD (Steinke et al., 2017).

For all tests, the null hypothesis represents that a trend was not identified. According to Goossens and Berger (1987), succession of precipitation records must be independent and probability distribution the same during the entire period for null hypothesis, identifying a stable climate. Hence, null hypothesis is accepted if the *p-value* is higher than α. The α value for all analyzed tests was determined to be 0.05, a common value for the significance test (Conover, 1999; Hipel and McLeod, 1994; McCuen, 2003; Rao and Hamed, 2019).

All tests were performed using standard libraries in Python as well as adaptations of publicly available code (Martino, 2009; SAS, 2020; Schramm, 2016).

4.3. **Results and discussion**

The results of the analysis are divided into five sections corresponding to each statistical method applied in this study along with a discussion. Mean seasonal values and the hydrological mean year (September to August) are shown in Table 4-1. As observed in the introduction, most of the rainfall happens in quarter DJF. Quarters SON and MAM display similar behavior because the first is the beginning of the wet season, and the second is the beginning of the dry season. Quarter JJA is the driest period of the year, registering lower rainfall values.

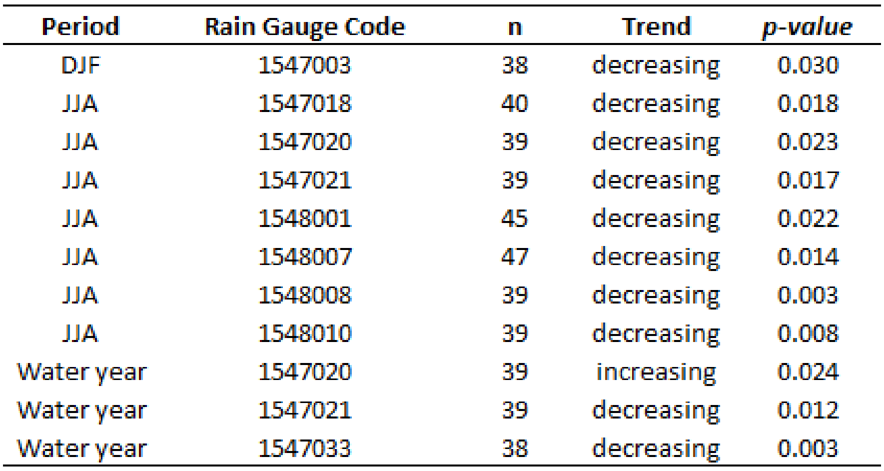
Table 4-1: Average Values in mm (1971-2017)

Period	Average
SON	393.9
DJF	651.5
MAM	347.0
JJA	22.5
Water Year	1414.9

4.3.1. MK results

Table 4-2 lists rain gauges where trends were identified using **MK**. In quarter DJF, a single station (1547003) presented a decreasing trend. This quarter is representative for the rainfall analysis since most of the rain occurs during this time. For quarter JJA, a decreasing trend was identified in seven gauges. However, this result does not affect water management since this period is classified as a dry season, and average value for this quarter is significantly lower than the other periods as observed in Table 4-1. Analyzing MK results related to the Water Year, 3 gauges registered trends. Gauge 1547020 presented an increasing trend and the other 2 gauges (1547021 - 1547003) exhibited decreasing trends. These last two also presented decreasing trends in quarters DJF (1547003) and JJA (1547021). Both gauges are not used for water supply and are located in urban or semi-urban areas. The overall results indicate that the percentage of gauges/periods displaying trends by the **MK** was 10.48%.

Table 4-2: MK Results for gauges rejected by the null hypothesis



Period	Rain Gauge Code	n	Trend	*p-value*
DJF	1547003	38	decreasing	0.030
JJA	1547018	40	decreasing	0.018
JJA	1547020	39	decreasing	0.023
JJA	1547021	39	decreasing	0.017
JJA	1548001	45	decreasing	0.022
JJA	1548007	47	decreasing	0.014
JJA	1548008	39	decreasing	0.003
JJA	1548010	39	decreasing	0.008
Water year	1547020	39	increasing	0.024
Water year	1547021	39	decreasing	0.012
Water year	1547033	38	decreasing	0.003

4.3.2. CS results

The results based on **CS** are summarized in Table 4-3. For quarter DJF, it is possible to see that, as in the **MK** test, a single gauge (1547020), had a decreasing trend. For quarter MAM, gauge 1547013 presented a decreasing trend, different from the **MK** results, where a trend was not identified in this period for any gauge. Quarter JJA also presented multiples gauges, 1547014, 1547019, 1547020, 1547021, 1548008, and 1548010, describing decreasing trends. The last four replicated behavior described in **MK**. Stations 1547021 and 1548006 were identified as having trends for the Water Year, and the first also repeated the classification obtained by the **MK**.

Table 4-3: **CS** Results for gauges rejected by the null hypothesis

Period	Rain Gauge Code	n	*p-value*	Trend	Positive Differences	Negative Differences
DJF	1547020	39	0.032	increasing	5	14
MAM	1547013	46	0.047	decreasing	16	7
JJA	1547014	39	0.048	decreasing	13	5
JJA	1547019	39	0.010	decreasing	15	4
JJA	1547020	39	0.048	decreasing	13	5
JJA	1547021	39	0.015	decreasing	14	4
JJA	1548008	39	0.010	decreasing	15	4
JJA	1548010	39	0.032	decreasing	14	5
Water year	1547021	39	0.032	decreasing	14	5
Water year	1548006	47	0.047	decreasing	16	7

Table 4-3 brings together the number of positive and negative differences, making it possible to see the magnitude of the trends. Chen and Huang (2020) presented an analysis based on these values, and the *p-value* to identify the degree of a trend. In this way, using the definition proposed by Chen and Huang (2020), some gauges that presented trends for **MK** could also be identified presenting some level of a trend for **CS**. Despite the null hypothesis being rejected, these gauges showed a high number of Positive Differences compared to Negative Differences in the **CS** as well as significant *p-value* (0.05 < *p-value* < 0.1). According to Chen and Huang (2020), this condition can be used to classify gauges as presenting a "Strong" trend while *p-value* < 0.05 would be considered "Extremely Strong". Table 4-4 depicts the gauges classified as "Strong", where most could be classified as trending by **MK**. Gauge 1548005 was an exception, and did not present a tendency for **MK**, displaying significant contrast between positive and negative differences.

Table 4-4: **CS** results for gauges accepted by the null hypothesis and Mann-Kendal results.

Rain Gauge Code	Period	n	*Mann-Kendall*	*p-value*	Positive Differences	Negative Differences
1547003	DJF	38	decreasing	0.084	13	6
1548001	JJA	45	decreasing	0.058	14	6
1548005	JJA	47	no trend	0.067	15	7
1548007	JJA	47	decreasing	0.067	15	7
1547020	Water year	39	increasing	0.084	6	13
1547003	Water year	38	decreasing	0.084	13	6

Following the classification proposed by Chen and Huang (2020), a "Weak" trend can be identified if 0.1 < *p-value* < 0.25. Six gauges presented a "Weak" trend for quarter DJF, three for quarter MAM, four for JJA, three in SON, and three for the

Water year. Gauge 158007 showed a weak trend for quarters DJF and JJA, and for the water year. This gauge is located in the watershed used for water supply. The overall results indicate that the percentage of gauges/periods displaying a trend by **CS** was 9.52%.

4.3.3. WW results

The **WW test** seeks to verify oscillations above and below the median, with each oscillation in a direction followed by an oscillation in a different direction counted as a run (Wald and Wolfowitz, 1940). Too few runs, i.e. the constant occurrence of values over/under the median, could be identified as trends in the median during the period analyzed (Thom, 1966). Hence, this test explains variations around the median. The results from the **WW** executed for the rainfall data which were considered as having trends are described in Table 4-5. Three gauges presented trends in quarter DJF, one in MAM, two in quarter JJA, and three in the SON quarter. From the nine rainfall figures presented in Table 4-5, only two were classified as having trends for the **CS**: 1547020 for quarter DJF and 1547014 for JJA. The trending gauges by the **WW** were not classified as trending by **MK** and vice-versa. Additionally, as **WW** can be used to test the independence of a dataset (Rao and Hamed, 2019), the results presented here reject the hypothesis of independent concern the gauges show in Table 4-5. The overall results indicate that the percentage of gauges/periods displaying a trend by the **WW** was 8.57%.

Table 4-5: **WW** results for gauges rejected by the null hypothesis

Period	Rain Gauge Code	n	z	p-value	Trend?	+ Runs	*- Runs*	n Runs
DJF	1547009	46	-2.11	0.035	Yes	23	23	17
DJF	1547014	39	-2.00	0.046	Yes	19	19	14
DJF	1548007	46	-2.11	0.035	Yes	23	23	17
MAM	1548005	48	-2.41	0.016	Yes	24	24	17
JJA	1547014	39	2.00	0.046	Yes	19	19	26
JJA	1547022	40	2.00	0.046	Yes	20	20	27
SON	1547008	46	-2.11	0.035	Yes	23	23	17
SON	1547018	40	-2.00	0.046	Yes	20	20	15
SON	1547033	38	2.33	0.020	Yes	19	19	27

4.3.4. SP results

Table 4-6 describes results of the **SP** test. Two gauges exhibited trends in quarter DJF: 1547020 and 1547003, increasing and decreasing, respectively. In quarter JJA, nine gauges presented decreasing trends, and for the water year, two gauges also presented a decreasing trend. According to Yue et al. (2002) the **SP** test, and the **MK,** should bring almost identical results. Of the thirteen gauges/periods presenting some type of trend, only three did not present a trend in the **MK**: 154720/DJF, 1547013/JJA, and 1548006/JJA. Others presented similar behavior in the **MK** test. The overall results indicate that the percentage of gauges/periods displaying a trend by the **SP** was 12.38%.

Table 4-6: **SP** Results for gauges rejected by the null hypothesis

Period	Rain Gauge Code	n	ρ	p-value	Direction
DJF	1547020	39	0.32	0.049	increasing
DJF	1547003	38	-0.35	0.029	decreasing
JJA	1547013	46	-0.29	0.047	decreasing
JJA	1547018	40	-0.37	0.019	decreasing
JJA	1547020	39	-0.38	0.019	decreasing
JJA	1547021	39	-0.40	0.014	decreasing
JJA	1548006	47	-0.30	0.043	decreasing
JJA	1548007	47	-0.37	0.012	decreasing
JJA	1548008	39	-0.49	0.00	decreasing
JJA	1548010	39	-0.47	0.00	decreasing
JJA	1548001	45	-0.35	0.020	decreasing
Water year	1547021	39	-0.41	0.010	decreasing
Water year	1547033	38	-0.47	0.003	decreasing

4.3.5. Water management from the perspective of a trending scenario

It can be seen that for all analyses described in the previous topics, there were mixed results. In order to group the statistics obtained by **MK**, **CS**, and **SP**, Table 4-7 was built. To help with visualization, **WW** statistics were not included. The only gauge classified as having a trend was also classified in the same way by **WW**. The percentage of gauges/periods identified as having a trend by at least one test was approximately 10%. From the trending points, 54% presented trends with only one method, 27% with two methods, and 19% with three methods. Hipel and McLeod (1994) suggested that non-parametric tests were not developed to show the magnitude of a certain statistical characteristic, but to indicate if there is some type of behavior. That is, non-parametric tests are considered to be exploratory data analysis procedures and can be a powerful tool for environmental analysis (Goossens and Berger, 1987; Rao and Hamed, 2019; WMO, 2009b). The results here, especially those depicted in Table 4-7, presented just one gauge (1547003) with decreasing trends during quarter DJF, the most important quarter for water management in our region of study, and it was identified by more than one test (**MK** and **SP**). As observed in the ***MK*** test, the site of this gauge is outside the watershed of the water supply reservoirs. Analyzing the water year, three gauges presented decreasing trends. All of them are located in urban areas that are not used for water supply. The location of trending gauges by period is depicted in Figure 4-2.

Understanding the exploratory characteristic of these tests, and their results could be a suitable condition for the study area related to the water supply. As mentioned in the introduction, a water scarcity event occurred in FD between 2016 and 2018. Lima *et al.* (2018) highlight the fact that during these three years, the gauge (1548007) located inside the basin most important for water supply, registered an average of 75% of the historic average. The cited gauge presented a decreasing trend behavior in JJA period for the **MK**, **SP**, and the **CS**, the latter considering the approach proposed by Chen and Huang (2020). It presented the same behavior in DJF period for the WW.

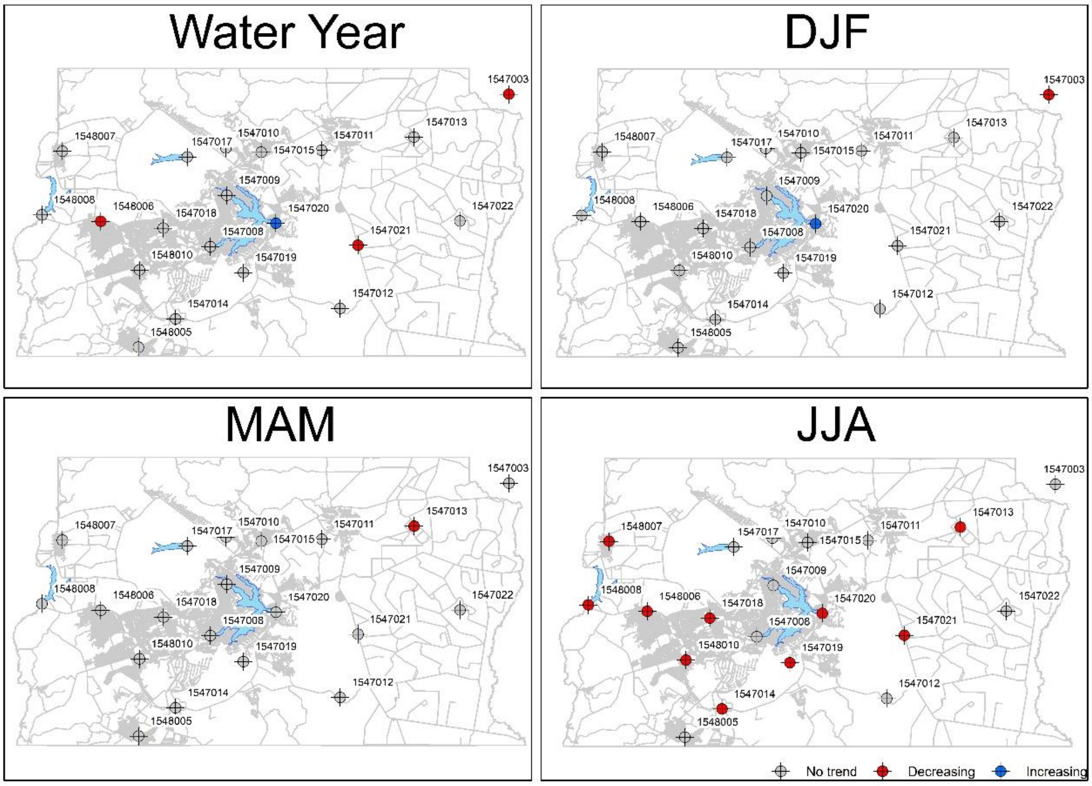


Figure 4-2. Trending rain gauges by quarters which presented trend and water year

Table 4-7: Gauges/periods identified as trending sites for **MK**, **CS**, and **SP**. The * means the only gauge which was classified as a trending site by **WW.**

Period	Rain Gauge Code	MK	CS	SP
DJF	1547003	decreasing	No	decreasing
Water year	1547003	decreasing	No	decreasing
JJA	1547013	No	No	decreasing
MAM	1547013	No	decreasing	No
JJA	1547018	decreasing	No	decreasing
JJA	1547019	No	decreasing	No
DJF	1547020	No	increasing	increasing
JJA	1547020	decreasing	decreasing	decreasing
Water year	1547020	increasing	No	No
JJA	1547021	decreasing	decreasing	decreasing
Water year	1547021	decreasing	decreasing	decreasing
JJA	1548001	decreasing	No	decreasing
JJA	1548006	No	No	decreasing
Water year	1548006	No	decreasing	No
JJA	1548007	decreasing	No	decreasing
JJA	1548008	decreasing	decreasing	decreasing
JJA	1548010	decreasing	decreasing	decreasing
JJA	1547014 *	No	decreasing	No

As observed by Alves *et al.* (2015), Anunciação, Walde, et al., 2014, Borges *et al.* (2016), and Costa et al. (2012), FD presents high spatial heterogeneity for rainfall data. These variations may also be present within the series as observed in the cited triennium. Moreover, the fact that the study area is located within a monsoon region can explain these variations (Deng et al., 2018). Yue *et al.* (2002), analyzing the power of **MK** and **SP**, identified that variations within a series mask the existence of a trend. They suggest that as variations increase, the power of the test reduces. Likewise, as skewness coefficient increases, trend detection rates also increase (Yue et al., 2002). In order to corroborate this point of view, skewness verification was performed (D'Agostino et al., 2020). From the analyzed gauges/periods, 70% were classified as highly skewed, 10% as moderately skewed, and 20% as symmetric (Bulmer, 1979). Gauge 1548007, for instance, presented moderate and high γ values (0.836, 0.537, 5.210, 1.659, and 0.886 for the periods DJF, MAM, JJA, SON, and Water year, respectively). Yue *et al.* (2002) suggest that the power of the test is affected by the site's characteristics when a trend exists, and this skewness can affect the results. Hamed and Ramachandra Rao (1998) also observe influences related to the autocorrelation factor throughout the data series, where positive/negative autocorrelations increase/decrease rejection of the Null hypothesis.

As **WW** verifies variations around the median, results can indicate great disparities throughout the series which may affect trend analysis. The definition used for a climatic trend based on Micthell (1966), and supported by Goossens and Berger (1987), points out that this type of trend is identified by a smooth and monotonic alteration of average value for the analyzed period. Therefore, instead of presenting a climatic trend condition, expected oscillations in the rainfall amounts can be suggested instead. As commented by WMO (2009), statistical tests serve to point to the significance of results but do not supply indubitable conclusions. So, it is recommended to search for other additional types of information in order to shed more light on the results. These considerations should be analyzed by decision-makers in order to effectively manage the water supply as significant variations in future years, especially for the trending sites, can be expected.

Studies point out a decreasing trend in the duration of the rainy season in monsoon region of South America (Carvalho et al., 2011; Zilli et al., 2019) and a decreasing in the volume of rainfall in the Amazônia in the last five decades (e.g., Agudelo et al 2019). In addition, Prado et al. (2021) identified changes in the variability of precipitation in Central Brazil associated with the influence of the Pacific Ocean. These observations may affect the amount of rain in FD.

4.4. **Conclusion**

The overall results indicate that the percentage of gauges/periods displaying trends by the **MK** was 10.48%, **CS** 9.52%, **SP** 12.38, and **WW** 8.57%. Of these gauges/periods, 70% were classified as highly skewed, 10% as moderately skewed, and 20% as symmetric.

A decreasing trend was observed for quarter JJA, but this time of year is not significant for the water supply. The results, especially those depicted in Table 4-7, showed just one gauge with decreasing trend during quarter DJF, the most important for water management. The tests did not produce similar results, and results from **WW** suggested great variation throughout the series which can affect trend analysis. Just one rain gauge (1547003) presented a decreasing trend for quarter DJF in more than one test (**SP**, **MK,** and **WW**, and for **CS**, when using the methodology proposed by Chen and Huang, 2020). As observed in the ***MK** topic*, the site of this gauge is outside the watershed of the water supply reservoirs. Analyzing the water year, three gauges (1547003: MK and SP, 1547021: MK, CS, and SP, and 1548006: CS) presented decreasing trends and all of them are located in urban areas.

Changes in variability, length of wet and dry seasons (Agudelo et al., 2019, Prado et al 2021), and shifts of the South Atlantic Convergence Zone during the last forty years (Zilli et al., 2019) could be related to the trends identified in DF rainfall. The results obtained by this study, as opposed to presenting a climatic trend condition, suggest expected oscillations in rainfall amounts. These considerations should be analyzed by decision-makers in order to better manage the water supply as significant variations in future years, especially for the trending sites can be expected.

4.5. **Appendix**

Table 4-8. Time span for the Gauges

Station	Start	End
1547008	1/1/1971	12/31/2017
1547009	1/1/1971	1/31/2018
1547010	1/1/1971	1/31/2016
1547011	1/1/1971	12/31/2009
1547012	1/1/1971	2/28/2010
1547013	1/1/1971	11/30/2017
1547014	1/1/1979	12/31/2017
1547015	1/1/1987	11/30/2017
1547017	1/1/1987	11/30/2017
1547018	1/1/1978	11/30/2017
1547019	6/1/1978	11/30/2017
1547020	9/1/1978	11/30/2017
1547021	9/1/1978	11/30/2017
1547022	12/1/1977	11/30/2017
1547003	9/1/1979	11/30/2017
1548001	6/1/1973	11/30/2017
1548005	12/1/1970	11/30/2017
1548006	3/1/1971	11/30/2017
1548007	3/1/1971	11/30/2017
1548008	9/1/1978	11/30/2017
1548010	9/1/1978	11/30/2017

4.6. **References**

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5. MODELING RESERVOIR VOLUME/OUTFLOW IN A WATERSHED FOR WATER SUPPLY USING THE SWAT MODEL

5.1. Introduction

The necessity for consistent management of the water supply, especially in water-scarce regions around the world, has become increasingly important due to continued population growth or climate change, and, in some cases, both conditions (Barnett et al., 2005; Kahil et al., 2015; Rockström et al., 2004). The balance between available water and social demands is a delicate one (Duan and Bastiaanssen, 2013). The construction of reservoirs for multiple purposes, especially to overcome the challenge of prolonged dry seasons is an important part of the strategy to manage this tradeoff (Biemans et al., 2011; de Araújo and Medeiros, 2013; World Commission on Dams, 2000). Globally, reservoirs represent approximately 10,800 km³ of water impoundment (Chao et al., 2008), adding around 40% to irrigation supply from surface water (Biemans et al., 2011). The reservoirs, depending on their size, can be operated as a within-year reservoir or as a multiyear, or carryover reservoir (McMahon and Adeloye, 2005; Wu and Chen, 2012). The first one spills at least once per year, and the reservoirs mostly fill up during wet seasons. On the other hand, in a multi-year reservoir, part of the water obtained in one year is carried over and used in subsequent years, and the spilling process is infrequent. storage depends on rainfall throughout the year for maintenance of volume. Within-year reservoirs, because of their small storage capacities, can allocate water over weeks, months, or seasons (Wu and Chen, 2012). However, multi-year reservoirs normally allocate water between wet and dry years. Understanding the demands and amount of available water are two important keys to water management. In general, reservoir volumes are assessed by mass balance estimations between inputs (rivers and rainfall) and outputs (abstractions, evaporation, losses, etc.) (WMO, 2009c). Hydrological models can play important roles in water resource management and help to forecast reservoir behavior. According to Yeh (1985), multiple purpose reservoirs tend to require optimization or simulation models to control release decisions. As Wurbs (2011) suggests, hydrological models (or river/reservoir system models) are required to assess institutional and physical water management systems, including special conditions of water demand (e.g. hydropower, fishery, supply, etc.) for each time step (generally daily, monthly and yearly).

According to Wurbs et al. (1994), reservoir system analysis models can be categorized into three types: Simulation, optimization, and combinations of the two. Wurbs et al. (1994) define an optimization model as a searcher, seeking an optimal condition following some type of objective function. On the other hand, simulation models are limited to predicting the behavior of a system based on certain conditions. Although they have different capabilities and philosophies, some solutions combine approaches where an optimization model can simulate numerous iterative executions or a simulation model that can use optimization to search for the best model. For an extensive review of reservoir models, we suggest USACE (1991), Fayaed et al. (2013), and Lin and Rutten (2016) who describe the different methods in detail. This current study opted for a combined solution, using the SWAT (Soil and Water Assessment Tool) model for simulation, which has proven its capability in reservoir/river modeling (Gassman et al., 2007) and the SWAT Cup (SWAT Calibration and Uncertainty Programs) program for optimization (Abbaspour et al., 2015b).

The SWAT model is a watershed scale, hydrologic and water quality model, which allows for continuous hydrological simulation over long periods operating on a daily time step (Neitsch et al., 2011) and has proved to be an effective tool for assessing water resources in many places around the world (Gassman et al., 2007). Additionally, it is open-source software written in FORTRAN, which allows for modifications and improvements to be easily made. It was also built to allow modeling of reservoir volumes and deposition of sedimentation, pesticides, bacteria, and nutrients (Neitsch et al., 2011). Also, it is possible to be used in water management process in different scenarios (Carvalho-Santos et al., 2017; Leta et al., 2017; Zanin et al., 2018; Zhang et al., 2012). However, due to current limitations, it is not possible to reproduce daily consumptive use variations in the SWAT model (Carvalho-Santos et al., 2017). Some studies just simulated inflows to the reservoir with SWAT and modeled the reservoir using other models (e.g. de Souza Dias et al., 2018; Emami and Koch, 2017; Kangrang et al., 2018), and other studies totally ignored the effects of reservoirs in their simulations (e.g. Jalowska and Yuan, 2019).

The two critical pieces of information needed for water management in reservoirs for water supply are forecasting storage volume trends and water inflows. The propensity of achieving this with a single model has many advantages and can simplify the process for decision-makers. In a complex hydrologic supply system, multiple demands can change throughout the year. Paying attention to the aforementioned limitations, and the necessity to combine reservoir volume prediction with water inflow to storage, the present study developed a solution by changing SWAT's source code, allowing for daily consumption as an input for the model. When there are significant withdrawals from the water supply, and when they vary throughout the simulation period, this type of information can be added to the modified model. In order to verify all possible settings in SWAT, we compared results from the simulation, ignoring reservoir insertion into the modeling process, using both the default and modified models. For latter, different optimization approaches were verified.

5.2. **Simulating reservoirs with SWAT**

SWAT treats reservoirs as an impoundment placed on the outlet of the main channel in a watershed (Neitsch et al., 2011). SWAT requires the specifications listed in Figure 5-1. for reservoirs, following the theory proposed by Ward and Elliot (1995). The *principal spillway* is responsible for carrying the frequent discharge; the *emergency spillway* is an open channel designed for moments in which flood flows exceed the capacity of the principal spillway, releasing water to prevent overflow; the *freeboard* is provided to prevent waves (Ward and Trimble, 2003). The SWAT model treats *freeboard* and *emergency spillway* as just one outflow. Hence, SWAT allows two options for water release: passing through the principal spillway or bypassing the emergency spillway. SWAT requires two specifications from these spillways, the reservoir area and reservoir volume, to control volume of the reservoir.

The principal equation used by the SWAT reservoir model (Neitsch et al., 2011) is described in equation 1:

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep} \qquad (1)$$

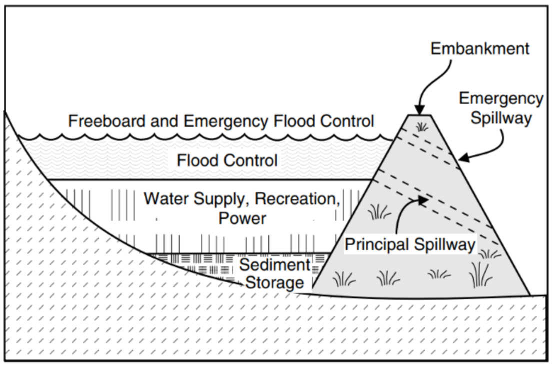

Figure 5-1: Attributes of a reservoir (adapt. from Ward and Trimble, 2003)

Where V is the volume of water in the reservoir at the end of the day (m^3H_20), V_{stored} is the volume of water stored in the impoundment at the beginning of the day (m^3H_20), $V_{flowout}$ is the water exiting from the reservoir (m^3H_20), V_{pcp} is water from the rain falling over the reservoir during the day (m^3H_20), V_{evap} is evaporated water from the reservoir during the day (m^3H_20), and V_{seep} is water lost from the impoundment during the day (m^3H_20). The SWAT model calculates all those elements at a daily time interval.

SWAT has four different methods of obtaining the $V_{flowout}$ in its default configuration, namely, as IRESCO: average annual rate for the uncontrolled reservoir (IRESCO = 0), measured monthly outflow (IRESCO =1), controlled outflow with target release (IRESCO = 2), and measured daily outflow (IRESCO = 3).

For *average annual rate for an uncontrolled reservoir*, the reservoir releases water when its volume exceeds the principal spillway volume. If the volume is greater than the principal spillway and less than the emergency spillway, SWAT uses Equations 2 and 3 (Neitsch et al., 2011):

$$V_{flowout} = V - V_{pr} \qquad if\ V - V_{pr} < q_{rel}.86400 \tag{2}$$

$$V_{flowout} = q_{rel}.86400 \qquad if\ V - V_{pr} > q_{rel}.86400 \tag{3}$$

If the volume exceeds the emergency spillway, SWAT uses Equations 4 and 5 (Neitsch et al., 2011):

$$V_{flowout} = (V - V_{em}) + \left(V_{em} - V_{pr}\right) \qquad if\ V_{em} - V_{pr} < q_{rel}.86400 \tag{4}$$

$$V_{flowout} = (V - V_{em}) + q_{rel}.86400 \qquad if\ V_{em} - V_{pr} > q_{rel}.86400 \tag{5}$$

Where V_{pr} is the volume of water contained in the reservoir when filled to the principal spillway (m^3H_20), q_{rel} is the average daily release rate (m^3/s) and V_{pr} is the volume of water contained in storage when filled to the principal spillway (m^3H_20). This option is ideal for reservoirs that have information about release rates, and when said release rates fluctuate very little throughout the year. In the present study, we used this option.

The two options for measured data (*measured monthly outflow* and *measured daily outflow*) are ideal for modelers who have historic data from streamflow gauges in the reservoir's outlet because the user must inform SWAT about said data. In the last option, *controlled outflow with target release*, the user must input data for the beginning and end of the flood season, allowing for establishment of a target volume. In that case, $V_{flowout}$ is specified as a function based on target volume defined by the user or calculated by SWAT, as a function of flood season and soil water content, and the number of days required to reach the target volume.

For all options, the user can set consumptive usage for all months in a year. However, SWAT assumes that consumptive use is a monthly average for the simulation years, i.e., the consumptive use in a month does not change from year to year. Thus, the user cannot create future scenarios that include changes in consumptive usage.

To overcome this limitation, the default SWAT model ($SWAT_{Def}$) was modified in this study ($SWAT_{Mod}$) allowing for the user to set monthly (or daily) consumptive usage throughout simulation years. Equation 1, which is used in *Res.f* file in the SWAT source code, was modified as shown in Equation 6.

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep} - V_{cons} \tag{6}$$

Where V_{cons} is the daily consumptive use. $SWAT_{res}$ requires a new text file containing daily (or monthly) rates for all simulation years.

5.3. Material and methods

5.3.1. Study area

The Santa Maria reservoir, located in the Federal District of Brazil (Figure 1), was selected to test this new routine. This lake is used to supply water to more than 21% of the city's population (GDF, 2017), and there is no hydropower generation functionality. A water crisis occurred in the city between 2016 and 2018, wherein the Santa Maria reservoir fell to less than 22% of its usable volume (Barcellos et al., 2018), and the FD government declared a state of emergency (GDF, 2017). The reservoir has just one spillway, the emergency spillway and all water is destined for the water supply and environmental purposes. Also, there is another small reservoir (a run-of-the-river reservoir) inside the watershed located below Santa Maria, but it was considered in this simulation due to its small dimensions. Catchment drainage area is mostly (over 95% of its watershed) preserved and protected by law. The city is located in the middle of Brazil, between parallels 15 and 16 (Figure 5-2). Reservoir capacity is 84.33 hm³ and the surface area for this volume is 794 ha. Its watershed contains a streamflow gauge at its outlet (Agência Nacional de Águas – ANA – code: 60477400) (Figure 5-2). The Federal District has an average annual precipitation of 1500 mm, however rain gauges in and around Santa Maria watershed present significantly different values, averaging 1245 mm (ANA codes: 01547017, 1548013, 1547010, 1548006, 1547009, 1547018 - Figure 5-2). The study area is also within a monsoon region, presenting two well-defined wet and dry seasons (Gan et al., 2004; Zhou and Lau, 1998). The rainy season is typically from November to April, and the dry season is from May to October.

5.3.2. Datasets and input data

The Santa Maria watershed was divided into 27 sub-basins according to the river system (Figure 5-3a). The identified land use classes (IBRAM, 2013) in the watershed are mostly (83%) forest (Savannah) and others (Figure 5-3b and Table 5-1). Elevation in the watershed varies from 750 m to 1344 m above mean sea level (Figure 5-3c) and the dominant soils in the watershed are Red Latosol, Yellow-Red Latosol, and Cambisol (Figure 5-3d).

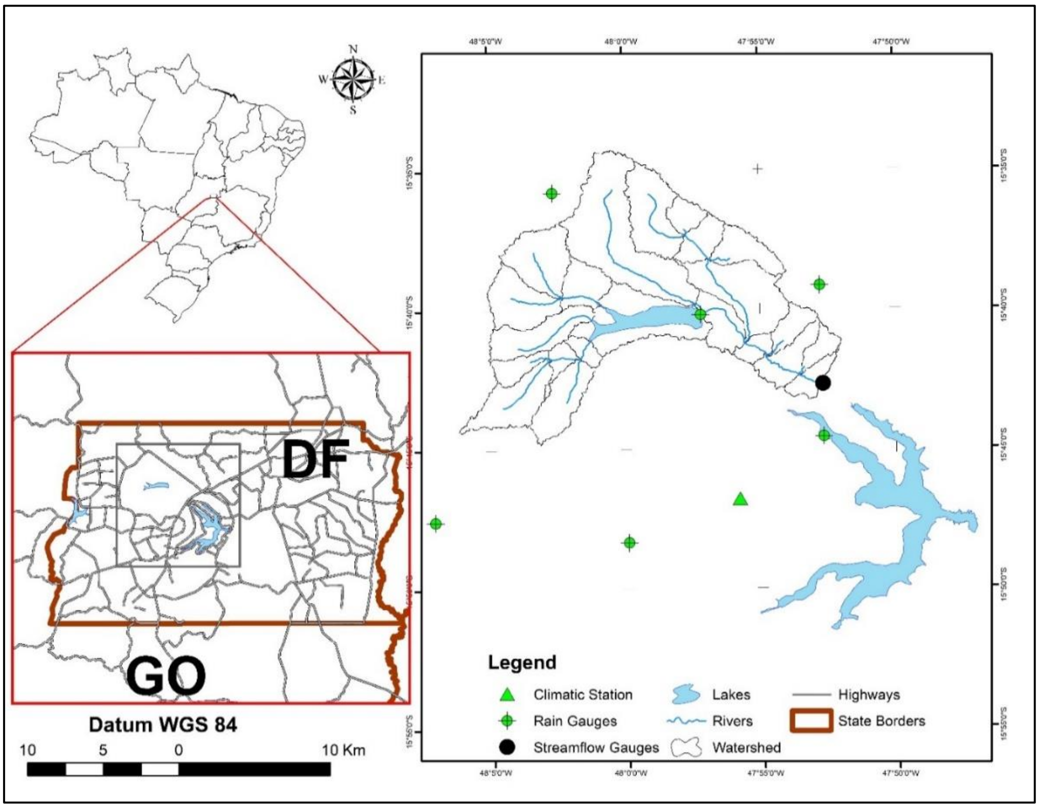

Figure 5-2. Study área

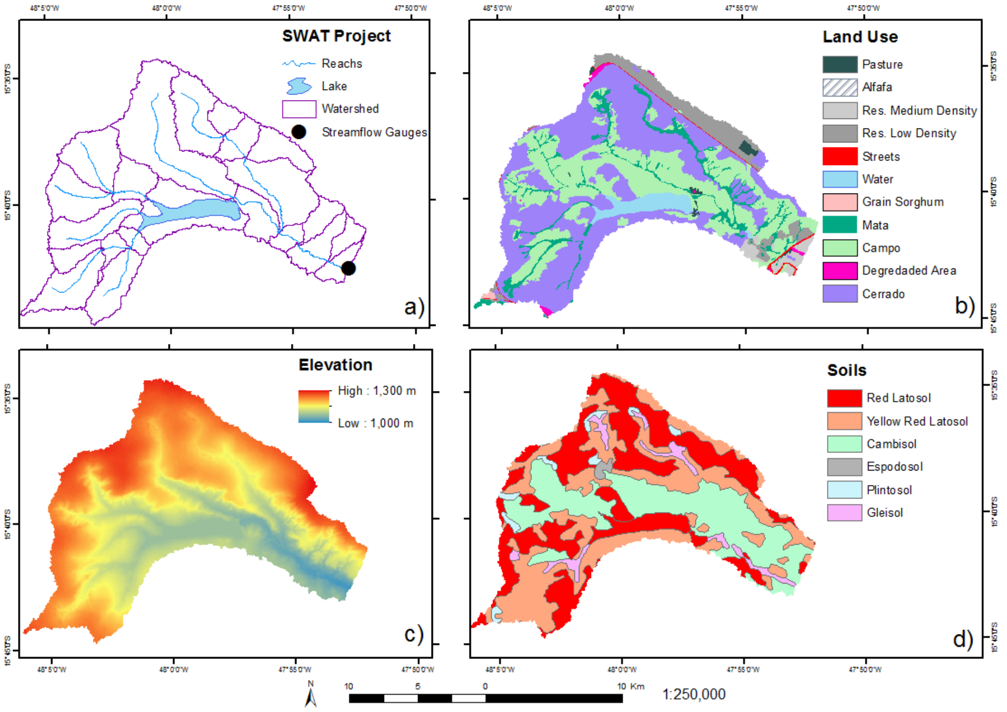

Figure 5-3: Spatial Data used in setting up the SWAT model at the Santa Maria Watershed: a) Sub-basins b) Land Use/Cover c) Topography d) Soil Map

The project elements are described in Table 5-1 describes the data source for all data used in this study. Soil properties were extracted from multiple sources, mostly journal papers focused on the Cerrado region. Figure 5-4 provides historical values concerning water consumption, rainfall, and watershed streamflows.

Table 5-1: Summary of geospatial and hydro-climatic characteristics

Project elements	Value
Watershed Area, km²	236
Number of sub-basins	27
Number of HRUs	361
Average annual rainfall, mm (1994-2006)	1245

Land use	% Area
Cerrado	43.87
Mata	7.40
Campo	32.41
Water	3.31
Other land uses	1.08

Table 5-2: Data source

Data	**Source**
Sub-basins (Figure 7-3a)	Generated in ArcSwat 10.5
Land Use/Cover map 30m (Figure 7-3b)	IBRAM, 2013
Digital Elevation Model (DEM) 30m (Figure 7-3c)	Shuttle Radar Topography Mission
Soil Map 1:100.000 (Figure 7-3d)	GDF and SEMA (2012)
Soil property data	Farias et al., (2008); Fiori et al., (2010); Lima et al. (2013); Lima et al., (2014); Reatto et al., (2000); Spera et al., (2005)

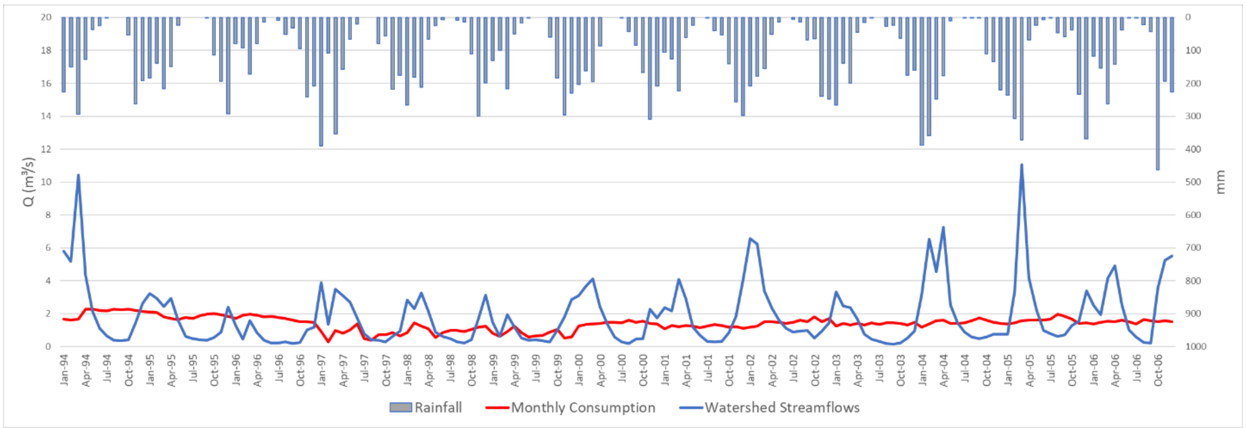

Figure 5-4. Historic water consumption, rainfall and watershed streamflows (1994-2006)

5.3.3. Swat model reservoir experiments

SWAT is a semi-distributed model applied to assess hydrological dynamics and reservoir modeling and has been utilized in a significant number of published scientific papers (Douglas-Mankin et al., 2010; Gassman et al., 2007; Tuppad et al., 2011). The way SWAT was built allows for changes to its publicly available source code, making it adaptable to many types of situations. To compare benefits of these changes to the SWAT code, five types of calibration procedures involving the two models were executed:

Table 5-3 Description related to each approach used in this work, split into two groups: SWAT_{Def} (Default) and SWATMod (Modified)

Approaches	Definition
SWATDef_no_Res_F	SWATDef model without reservoir inclusion or consumptive use, and by means of streamflows as reference for calibration process (Zhang et al., 2012)
SWATDef_w_Res_F	SWATDef model with the reservoir included in the project and also using streamflows for calibration
SWATMod_w_Res_F	SWATMod with the reservoir included in the project and using the streamflows for calibration
SWATMod_w_Res_RF	SWATMod with the reservoir included in the project and using streamflows and the reservoir for calibration
SWATMod_w_Res_R	SWATMod with the reservoir and calibration using just the reservoir

The first procedure was an attempt to verify the importance of reservoir inclusion in SWAT models. The last three approaches sought to verify the best solution for maintaining good agreement between the reservoir's volume and streamflows.

The period from 01/01/1994 to 12/31/2006 was chosen as the simulation period to compare results with Strauch and Volk (2013) who modeled the same watershed using SWAT. All SWAT models were calibrated and validated using, as input data, monthly streamflow measurements from 01/01/2001 to 12/31/2006 and from 01/01/1994 to 12/31/2000, respectively including a three-year warm-up period.

5.4. **Model performance assessment**

Five efficiency criteria were used to verify goodness-of-fit characteristics of the SWAT model as suggested by Moriasi et al., (2015) and Krause et al. (2005), based on performance ratings by Moriasi et al. (2015), Abbaspour (2015), Santhi et al. (2001) and Van Liew et al., (2003). The Nash-Sutcliffe efficiency (*NSE*) (Nash and Sutcliffe, 1970), Percent Bias (*PBIAS*), and Coefficient of Determination (R^2) were used as statistical metrics to compare observed and simulated data for streamflow and reservoir volume. Note that the performance criteria given in Table 5-4 were developed for streamflow. We used it for reservoir volume as well, however with caution.

Table 5-4: Performance Evaluation Criteria (adapt. from Moriasi et al., 2015).

Measure	Very Good	Good	Satisfactory	Not Satisfactory
R^2	$R^2 > 0.85$	$0.75 < R^2 \leq 0.85$	$0.60 < R^2 \leq 0.75$	$R^2 \leq 0.60$
NSE	$NSE > 0.80$	$0.70 < NSE \leq 0.80$	$0.50 < NSE \leq 0.70$	$NSE \leq 0.50$
PBIAS (%)	$R^2 < \pm 5$	$\pm 5 < PBIAS \leq \pm 10$	$\pm 10 < PBIAS \leq \pm 15$	$PBIAS \geq 15$

The SWAT CUP program (SWAT Calibration and Uncertainty Program) was chosen to run the automatic calibration process. SUFI2 routine (Sequential Uncertainty Fitting version 2), included in SWAT CUP, was selected as the method to generate random parameter values. SUFI2 is based on a stochastic concept applying Latin Hypercube Sampling to create n sets based on a given range inputted by the user.

Four SWAT Cup projects were created, and 500 sets were generated for each project. As a general rule, the SWAT CUP manual recommends 3 iterations for its projects (Abbaspour et al., 2015). Each calibration procedure was performed until satisfactory results were reached and/or the efficiency criteria had not shown significant improvements between two successive iterations (Abbaspour et al., 2015b).

The SWAT CUP program provides two more efficiency criteria: *r-factor* and *p-factor*. The goal of these metrics is evaluation of the envelope containing all simulated results generated by the calibration (validation) process, including the best simulation. These metrics help to identify the 95% prediction uncertainty (95 PPU) of a model, and map uncertainties on the parameters. The *p-factor* gives the percent of observed data falling inside the 95% prediction interval (95PPU), where 1 indicates 100% bracketing, and 1- *p-factor* would be the model error (Abbaspour et al., 2017). The *r-factor* is the "ratio of the average width of the 95PPU band and standard deviation of the measured variable" (Abbaspour et al., 2015b), i.e. the thickness of the 95PPU band (Abbaspour et al., 2017). Abbaspour *et al.* (2015) recommend *p-factor* ≥ 0.7 and *r-factor* ≤ 1.5 as adequate values. Both measures need to be evaluated together since low *r-factor* values (≤ 1.5) do not signify satisfactory results with *p-factor* values ≤ 0.7. Low *r-factor* values indicate low variance for all simulations generated during the calibration (validation) process while the *p-factor* search measures uncertainty for these simulations (Abbaspour et al., 2015b).

Additionally, a baseflow analysis was conducted using the WHAT (Web-based Hydrograph Analysis Tool system) program (Lim et al., 2005). A significant portion of streamflow could be contributed by baseflow, especially during certain periods, and its quantification is highly significant for sustainable water exploitation.

5.5. Results and Discussion

5.5.1. Analyzing the evaluation measures

Results from the evaluation measures concerning the five models are summarized in Table 5-5**Erro! Fonte de referência não encontrada.**, and monthly streamflows and reservoir volumes are depicted in Figure 5-5**Erro! Fonte de referência não encontrada.** and Figure 5-6, respectively. In Figure 5-6, the models where reservoir is included have two rows, one for the evaluation measure applied to streamflow, and another applied to reservoir volume. Bold values represent the best results for streamflow and reservoir volume.

The first approach ($\text{SWAT}_{\text{Def\_no\_Res\_F}}$), during the calibration period, presented "good" performance for R^2 ($0.75 < R^2 \leq 0.85$), *NSE* ($0.50 < NSE \leq 0.70$) and *PBIAS* ($\pm 5 < PBIAS \leq \pm 10$). The *p-factor* and the *r-factor* yielded adequate values (*p-factor* ≥ 0.7 and *r-factor* ≤ 1.5). In contrast, for the validation period, all evaluation measure values decreased significantly, being classified as "unsatisfactory" and "inadequate". Figure 5-5 supports this result, where it is possible to see that simulated streamflows are underestimated for the validation period. This approach, the only one where the reservoir option is not included, allows us to say that impacts on storage during the period from 01/01/2001 to 12/31/2006 could have been alleviated by the calibration process because this procedure can counterbalance simulated values that assign unrealistic values to the parameters. This position can be reinforced when observation of the validation results describes poor estimates compared to calibration results. This fact highlights the importance of taking into account reservoirs in the modeling process using SWAT, and how the calibration process can compensate for lack of information (consumptive use and reservoir existence for instance), leading to unrealistic results.

Table 5-5: Performance of different models in predicting monthly streamflows and reservoir volumes

Project	**Calibrated Variable**	Calibration (2000 - 2006)					Validation (1994 - 1999)				
		R2	NSE	Pbias	*p-factor*	*r-factor*	R2	NSE	Pbias	*p-factor*	*r-factor*
$\text{SWAT}_{\text{Def\_no\_Res}}$	Streamflow	0.74	0.73	6	0.92	1.77	0.60	0.52	16	0.75	1.81
$\text{SWAT}_{\text{Def\_w\_F}}$	Streamflow	0.82	0.80	7	0.89	1.19	0.08	-0.03	-9	0.78	1.40
	Reservoir	0.17	-0.18	-2	-	-	0.04	-0.74	0	-	-
$\text{SWAT}_{\text{Mod\_w\_F}}$	**Streamflow**	**0.87**	**0.85**	**0**	**0.85**	**1.04**	**0.61**	**0.52**	**-8**	**0.76**	**1.64**
	Reservoir	0.52	-7.29	9	-	-	0.70	-14.78	38	-	-
$\text{SWAT}_{\text{Mod\_w\_RF}}$	Streamflow	0.79	0.71	-8	0.79	1.20	0.33	0.04	-55	0.54	1.20
	Reservoir	**0.76**	**0.76**	**0**	**1.00**	**4.44**	**0.82**	**0.68**	**1**	**0.65**	**3.45**
$\text{SWAT}_{\text{Mod\_w\_R}}$	Streamflow	0.00	-0.18	-20	-	-	0.06	-0.19	-48	-	-
	Reservoir	0.74	0.73	0	1.0	7.3	0.80	0.74	0	1.00	3.31

The second approach ($\text{SWAT}_{\text{Def\_w\_Res\_F}}$) presented similar results for streamflow (in comparison with $\text{SWAT}_{\text{Def\_no\_Res\_F}}$) during the calibration period, yielding "good" performance for all measures, and good agreement with monthly streamflow (Figure 5-5). However, measures for reservoir volume, except for *PBIAS*, are poor and are considered unsatisfactory. The *p-factor* and *r-factor* were not calculated by SWAT CUP for the reservoir, because it was not used as a calibration reference. The default SWAT did not realistically capture reservoir behavior, and this is clear because consumption rates changed considerably throughout the analyzed period. Figure 5-6 helps to clarify this issue since average monthly historic consumption required by SWAT default did not reflect actual consumptive use for this reservoir. During the validation period, R^2 and *NSE* results for both variables were considered "unsatisfactory" ($R^2 \leq 0.60$, $NSE \leq 0.50$) and *PBIAS*, *p-factor*, and *r-factor* concerning streamflows were considered "good" and "adequate". Adequate performance for these last two criteria signifies a high percentage of observation points, bracketed by the prediction uncertainty band created by the simulations for this approach. R^2 and *NSE* were strongly affected by high consumptive use in the validation period because consumptive usage was considered a constant average monthly level. The best results for the calibration period showed again that the calibration process helps alleviate deviation due to consumptive use. For both periods, the *PBIAS* measure was considered "very good" for the reservoir. This result, associated with streamflow time series depicted in Figure 5-5 shows that *PBIAS* can not be considered as the only evaluation measure (Moriasi et al., 2015). Greater deviation during the high peaks was compensated by good-agreement during low peaks, despite having years with extreme deviation (1995-1997).

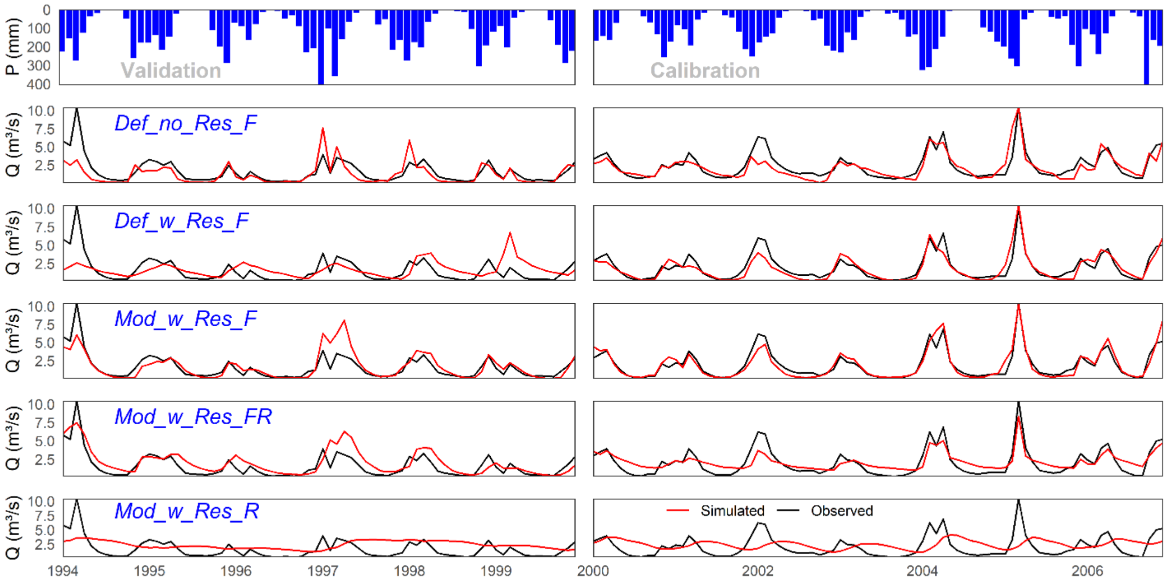

Figure 5-5: Monthly streamflows from all approaches

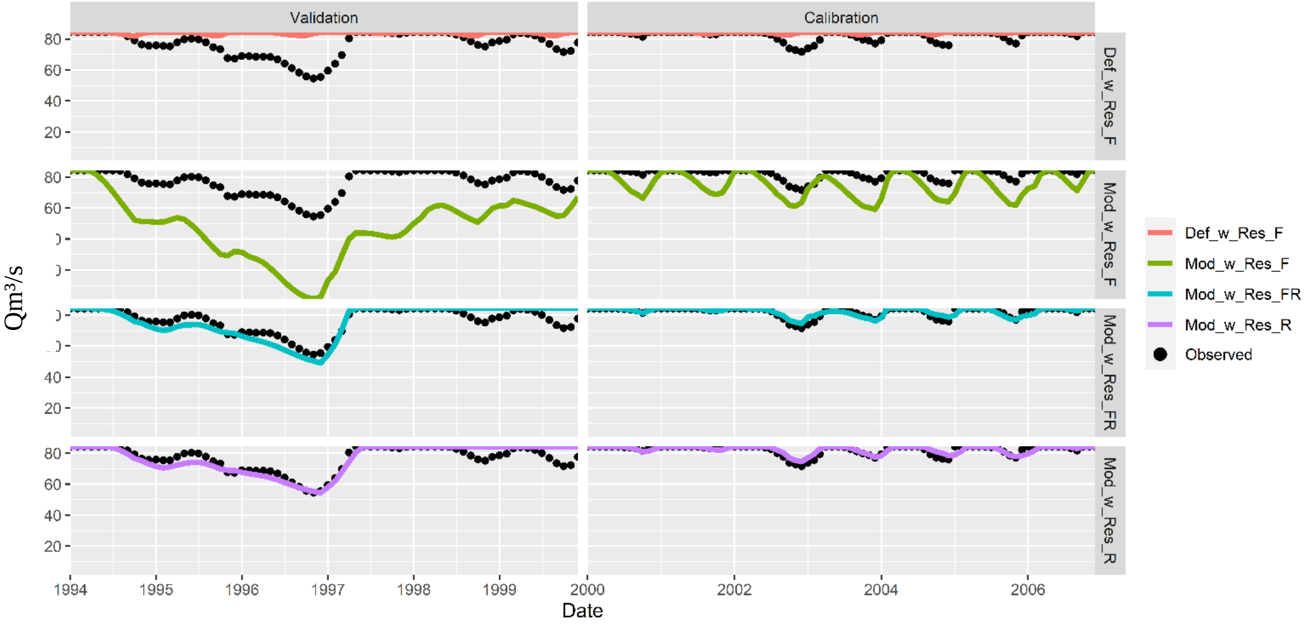

Figure 5-6: Reservoir's volumes from all approaches

The third approach ($\text{SWAT}_{\text{Mod\_w\_Res\_F}}$) was the best for streamflows. All evaluation measures yielded either "very good" or "adequate" performance for the calibration period. For the validation period, the quality of the results reduced but achieved "satisfactory" and "adequate" performance (*PBIAS* was considered "good") except for the *r-factor*. The modified SWAT showed that inclusion of actual consumptive use improved correlation. Reservoir volume was also strongly affected by this model. Visual inspection of Figure 5-6 shows that the simulated storage is very similar to that observed. However, the fact volume was not used for calibration created one big peak streamflow for the validation period. The extreme shortage in this period helps explain this fact, as calibration was done for an average rainfall interval. From 1994 to 1995, El Niño effects contributed to a reduction in rainfall quantity throughout the city and the reservoir reached its lowest historic level during this period (GGWeather, 2020; Lima et al., 2018). Except for R^2 in the validation period, all criteria were considered "unsatisfactory". The *p-factor* and *r-factor* were not calculated by SWAT Cup for the reservoir, for the same reasons explained in the second approach.

The fourth approach ($\text{SWAT}_{\text{Mod\_w\_Res\_RF}}$) produced "good" and "adequate" performance for streamflow and reservoir for the calibration period. Except for some measures concerning the reservoir where *PBIAS* and *r-factor* were considered as “very good” and “inadequate”. The high values obtained by *r-factor* can be analyzed as a great variance in the results obtained by all simulations in the last iteration of this approach. On the other hand, *p-factor* received the maximum value (*p-factor* =1), signifying that all measured data is bracketed by the 95PPU band. The simultaneous calibration improved results for both variables for the calibration period. However, during the validation period, performance for streamflow was reduced and was classified as “unsatisfactory”. The *r-factor* was the only criterion concerning streamflows that received an “adequate” classification, indicating low variance, however, the low value obtained for *p-factor* indicates a high level of uncertainty for this approach related to streamflows. In contrast, reservoir results were classified as “satisfactory”, “good”, and “very good” for *NSE*, R^2, and *PBIAS*, respectively. Additionally, the *p-factor* result (<0.70) describes some degree of uncertainty and the high value associated with *r-factor* brings high variation to the simulations. This approach, $\mathrm{SWAT}_{\mathrm{Mod\_w\_RF}}$, demonstrated that the inclusion of the reservoir as a variable in the calibration process can improve model performance for storage volumes, but may negatively affect modeling performance of streamflows.

The measures evaluated for the last approach ($\mathrm{SWAT}_{\mathrm{Mod\_w\_Res\_RF}}$), which focused on the reservoir, performed very well for volume storage in the calibration period as well as the validation period. *NSE* and *PBIAS* had the same responses for both analyzed periods (“good” and “very good”, respectively). R^2 yielded “satisfactory” performance for the calibration period and “good” for validation. The *p-factor* obtained the same value for both analyzed periods, evaluated as adequate with the maximum factor (*p-factor* =1). In contrast, the *r-factor* yielded high values, indicating great uncertainty for the evaluated parameter sets. Streamflows received the worst classification compared to other approaches, being “unsatisfactory” for both periods. Looking at Figure 5-6, $\mathrm{SWAT}_{\mathrm{Mod\_w\_Res\_R}}$ and $\mathrm{SWAT}_{\mathrm{Mod\_w\_Res\_RF}}$ results performed similarly related to storage volumes for the calibration and validation intervals. The maximum value obtained by the *r-factor* in the $\mathrm{SWAT}_{\mathrm{Mod\_w\_Res\_R}}$ for both analyzed periods indicates better results for this approach. On the other hand, simulated streamflow showed significantly reduced performance, especially for the validation portion.

Strauch and Volk (2013) applied another modified version of the SWAT model to the Santa Maria watershed during two periods, from 2000 – 2006 (calibration) and 1991 – 1999 (validation), obtaining the following values for *NSE*, R^2, and *PBIAS* for the calibration (validation) period: 0.79 (0.66), 0.78 (0.67), -2.7 (5.9), respectively. They did not provide performance measures for the default version or explain how the reservoir was dealt with in their model. Moreover, they used consumptive use as a daily average for the analyzed period. The model proposed by Strauch and Volk (2013) consisted of modifications to the evapotranspiration method present in SWAT for perennial vegetation in the tropics. Table 5-6 describes the comparison between the main results from Strauch and Volk (2013) and $\text{SWAT}_{\text{Mod\_w\_Res\_F.}}$

Table 5-6. Comparison between the results from Strauch and Volk (2013) and $\text{SWAT}_{\text{Mod\_w\_Res\_F.}}$

	Calibration			Validation		
Models	*NSE*	R^2	*PBIAS*	*NSE*	R^2	*PBIAS*
Strauch and Volk (2013)	0.79	0.78	-2.7	0.66	0.67	5.9
$\text{SWAT}_{\text{Mod\_w\_Res\_F}}$	0.85	0.87	0	0.52	0.61	-8

5.5.2. Flow duration curves

Figure 5-7 and Figure 5-8 depict flow duration curves for the calibration and validation periods, respectively. During calibration (Figure 5-7) the modified models where streamflows were used as a reference to calibrate ($\text{SWAT}_{\text{Mod\_w\_Res\_R}}$ and $\text{SWAT}_{\text{Mod\_w\_Res\_RF}}$) overestimated low and average and low ($Q < 4m^3/s$) more than 65% of the time. The $\text{SWAT}_{\text{Mod\_w\_Res\_R}}$ also presented poor goodness-of-fit for high streamflows ($Q > 4m^3/s$) and $\text{SWAT}_{\text{Mod\_w\_Res\_RF}}$ performed slightly better. Other models presented similar trends with $\text{SWAT}_{\text{Def\_no\_Res\_F}}$ as having the best performance. In general, models follow high streamflows but underestimate the low. Calibration procedures using only streamflows as a reference generated the best performance compared to options using the reservoir only or reservoir and streamflows together.

For the validation period (Figure 5-8), $\text{SWAT}_{\text{Mod\_w\_Res\_R}}$ performed worst, underestimating high streamflows and overestimating low streamflows over 85% of the time. $\mathrm{SWAT}_{\mathrm{Mod\_w\_Res\_RF}}$ achieved better performance than in the calibration period, however, this model slightly overestimated streamflows in all cases. $\mathrm{SWAT}_{\mathrm{Def\_w\_Res\_F}}$ underestimated high streamflows and overestimated the low streamflows which was different than observed for the calibration period. $\mathrm{SWAT}_{\mathrm{Def\_no\_Res\_F}}$ underestimated streamflows for all time periods, with slight differences observed for high streamflows and greater differences in low streamflows. $\mathrm{SWAT}_{\mathrm{Mod\_w\_Res\_F}}$ performed well 70% of the time and underestimated extremely low streamflows (0.5 m^3/s).

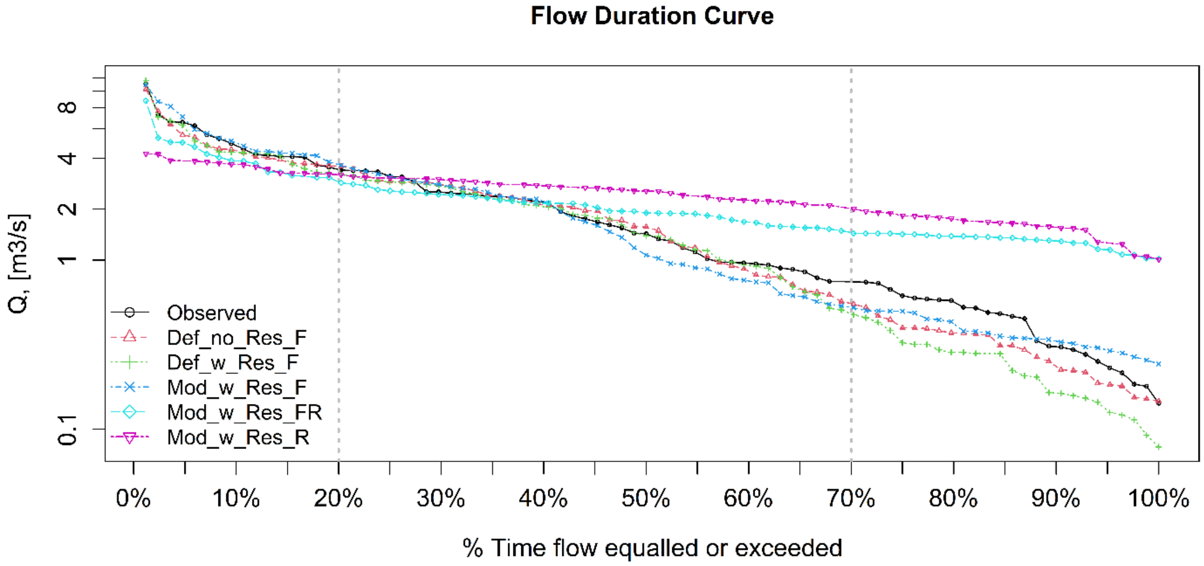

Figure 5-7: Flow duration curve of daily streamflow for the calibration period

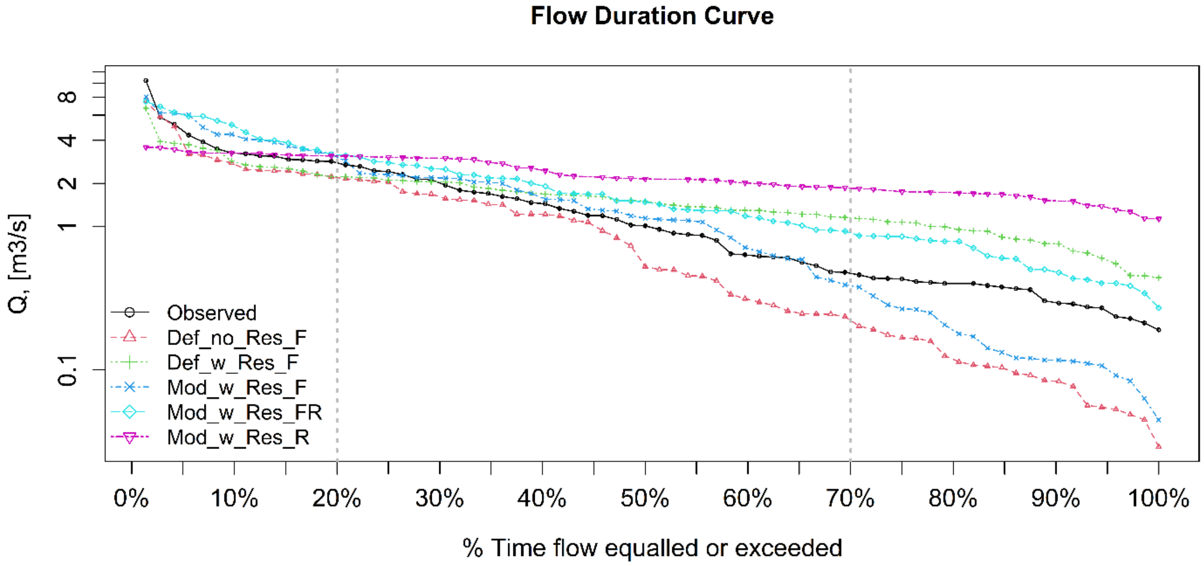

Figure 5-8: Flow duration curve of daily streamflow for the validation period

5.5.3. Baseflow

As the study area has two well-defined seasons (Gan et al., 2004; Zhou and Lau, 1998), the baseflow assumes the main role of water storage during the wet season and late release during the dry season (Ponce and Lindquist, 1990). Based on that information, baseflow was generated for both periods to identify the most appropriate model for representing this hydrologic element. The results from the WHAT program (Lim et al., 2005) are depicted in Figure 5-9 and Table 5-7. The modified versions that use the reservoir as a reference for calibration ($\text{SWAT}_{\text{Mod\_w\_Res\_R}}$ and $\text{SWAT}_{\text{Mod\_w\_Res\_RF}}$) overestimated baseflow for both periods, presenting the worst results according to the evaluation metrics. The default versions ($\text{SWAT}_{\text{Def\_no\_Res\_F}}$ and $\text{SWAT}_{\text{Def\_w\_Res\_F}}$) showed slight improvement compared to the modified versions using reservoir as a reference, and underestimating streamflows. However, the results obtained by the default versions did not present satisfactory performances, especially for the validation period. The $\text{SWAT}_{\text{Mod\_w\_Res\_RF}}$ was the best model, being classified at as satisfactory for all evaluation measures.

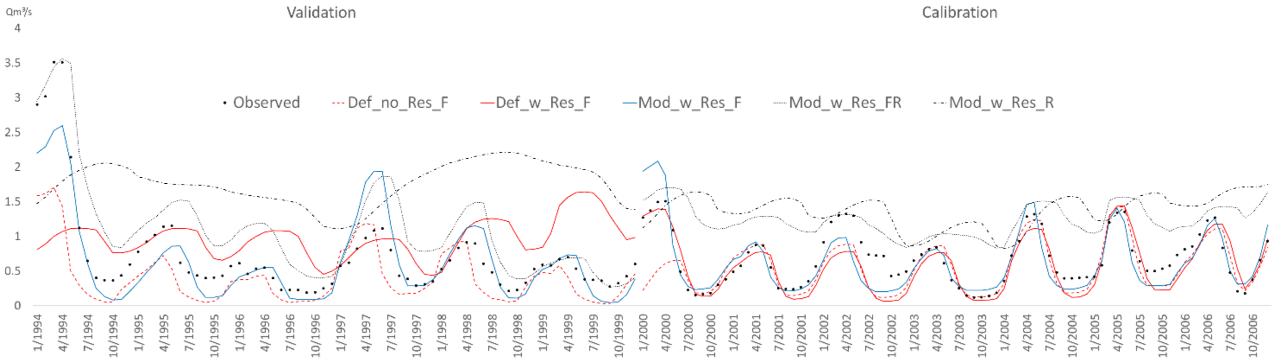

Figure 5-9: Baseflow for calibration and validation including observed and simulated data

Table 5-7: Results from the evaluation measures applied in the baseflow analysis

	Calibration			Validation		
	R²	Pbias	NSE	R²	Pbias	NSE
Def_no_Res_F	0.54	19%	0.40	0.67	43%	0.42
Def_w_Res_F	0.71	15%	0.60	0.00	-35%	-0.25
Mod_w_Res_F	0.74	7%	0.63	0.77	10%	0.76
Mod_w_Res_FR	0.33	-83%	-1.78	0.80	-56%	0.42
Mod_w_Res_R	0.01	-102%	-3.69	0.00	-145%	-2.54

5.6. **Conclusions**

The results described in this study help to understand SWAT's behavior associated with watersheds containing reservoirs. The evaluation measures applied to the simulated streamflows highlight, both, that the default SWAT model has some limitations in handling storage with consumptive use, and how reference choices for the calibration procedure can impact results. The results for baseflow reinforce the evaluation obtained by flow duration curves. Analyzing both periods, $\mathrm{SWAT}_{\mathrm{Mod\_w\_Res\_F}}$ achieved the best performance with stress on the importance of including reservoirs and consumption information in the model. Another significant point is the necessity of the streamflows to be used as reference for the calibration when the focus is on rivers. Conversely, if the focus is on reservoirs, reservoirs should be considered during calibration. Depending on the case, creation of two SWAT Cup projects, one for each reference, may be a good solution. Moreover, an operational objective as described by Salas and Hall (1983) and WMO (2009), creating rule curves aimed at the water supply can be developed and supported by the SWAT model. This possibility enhances the performance of water management systems, allowing for more planning and forecasting tools.

The present study modified the SWAT source code to allow daily or monthly consumptive use from reservoirs, a feature not available in the SWAT default model. The modified version ($\mathrm{SWAT}_{\mathrm{Mod}}$) and default version ($\mathrm{SWAT}_{\mathrm{Def}}$) were both tested in a monsoon region located in Brazil using different approaches. For $\mathrm{SWAT}_{\mathrm{Def}}$ two approaches were evaluated: i) reservoir and consumptive use were not considered in the model; ii) reservoir was considered in the model and consumptive use was set to default version requirements. For $\mathrm{SWAT}_{\mathrm{Mod}}$, consumptive use was set as monthly based on historical data and three possibilities of reference for the calibration procedure were evaluated. Also, the reservoir was considered in all approaches: i) streamflows as calibration target; ii) streamflows and the reservoir as the reference; iii) reservoir as the reference.

The simulated streamflows were evaluated by the commonly used performance Pbias, R^2, and NSE, as well as two uncertainty measurements offered by SWAT Cup: *p-factor* and *r-factor*. Flow duration curves and baseflow were also generated for the simulated streamflows as part of the assessment. From the results, three conclusions could be drawn: i) ignoring reservoirs can be a great source of errors in modeling watersheds; ii) the modified model ($SWAT_{Mod}$) can considerably improve performance for basins containing a reservoir with high, dynamic consumptive use; iii) depending on the necessity of the users (information about rivers or reservoir), isolated calibrations using reservoir or streamflows as a reference should be considered an opportunity to improve the results for modeling in watersheds containing water storages.

The required consumption file for modified SWAT versions is also easy to build. This data can be organized as a monthly or daily period in a single text file where each bit of data should be put into a specific row.

5.7. **References**

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6. APPROACHES FOR HYDROLOGIC MODELLING ACCOUNTING FOR SPATIAL RAINFALL VARIABILITY IN MONSOON REGIONS

6.1. Introduction

Although Brazil contains 12% of the planet's freshwater (FAO, 2003), there is considerable heterogeneity in the water resource availability and rainfall distribution (e.g., 80% of this water is concentrated in the Amazon Region) (Tucci et al., 2001). Some portions of the country are situated within a monsoon region (Wang et al., 2011a), creating a challenge for the planning and management of this precious resource. Hydrologic models are essential tools to support water resource management, and have been used worldwide (Singh and Frevert, 2006) due to their effectiveness for decision making (Beven, 2001), especially watershed models designed for understanding and managing complex watershed systems and river basins (Li et al., 2018). Although there are some limitations and restrictions in hydrologic modeling related to many factors as initial and boundary conditions (generally poorly known) or uncertainties due to modeling approaches (Beven, 1993), hydrological models are still an important tool for water management (WMO, 2009). And methods have been developed to reduce these issues and improve results (Liu & Gupta, 2007). Also Hydrologic modeling for monsoon regions is considered a complicated task (Annamalai et al., 2007; Colman et al., 2011) since these areas are known to have complex hydrologic processes due to seasonal climatic variations (Turner et al., 2011) and dominant convective rainfall during the precipitous season (McGregor and Nieuwolt, 1998; Wang et al., 2011b).

Processed-based hydrologic models typically include multiple processes, such as infiltration, surface runoff, lateral flow, baseflow, evapotranspiration, percolation, etc., which vary from one watershed to another (Fatichi et al., 2016). Since rainfall is the most critical input driving hydrological models, dealing with spatial variability of precipitation becomes the biggest challenge in producing reliable hydrologic estimates and predictions (Bardossy and Das, 2008; Dawdy and Bergmann, 1969; J. Cho et al., 2009). Distributed watershed models such as the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) are capable of handling the heterogeneity in landscapes by varying parameter values and utilizing input forcing, assigned to different portions of the watershed (Aral and Gunduz, 2006). In this context, the availability and quality of spatially and temporally variable rainfall data is critical in hydrologic modeling (Chaplot et al., 2005; Huff, 1970; Osborn et al., 1972).

Previous studies have shown that a lack of spatially distributed rainfall data is a limiting factor for model performance (Hernandez et al. 2000), and the uncertainty of hydrologic modeling increases exponentially as the number of rain gauges decrease (Cho *et al*. (2009)). Therefore, areas receiving intense rainfall with high spatial heterogeneity should have a dense network of rain gauges (Hernandez *et al.* 1997). Despite this recommendation, the quantity of ground-based rain gauges has decreased since the 1970s, contributing to a scenario where sparse rain gauge systems are a reality in many parts of the world (New *et al.* (2001)) (Huff, 1970; Osborn et al., 1972). The World Meteorological Organization (WMO) (2008) recommends a minimum density of 1 recording gauge per 5,750 km² for interior plains and 1 per 2,500 km² for mountains. Although the number of ground-based rain gauges has in fact decreased, emerging precipitation data from other sources has increased over the past several decades. Satellite-derived Precipitation Estimates (SPE), especially fused multi-satellite/gauge products, are a potential alternative to overcoming limitations related to low density of rain gauges and can be especially suitable for ungauged watersheds (Kidd and Levizzani, 2011). Both approaches (ground-based rain gauges and SPE) present advantages and disadvantages. For instance, remote-sensing derived data offers good spatial coverage while the number of covered years is usually lower (e.g., from the 1970s to the present), and there are biases and high variability associated with the information (New et al., 2001). Franchito et al. (2009) found good correlation between ground-based precipitation data and the TRMM (Tropical Rainfall Measuring Mission) PR (Precipitation Radar) product (3A25G2) in Brazil, but biases are large in central Brazil, an area partially classified as a monsoon region (Gan et al., 2004). In order to minimize biases of satellite precipitation products, Beck *et al*. (2017a) and Funk *et al*. (2015b) developed the Multi-Source Weighted-Ensemble Precipitation (MSWEP) version 2 and the Climate Hazards Group Infrared Precipitation with Station data (CHIRPS) respectively. Both solutions are hybrid rainfall products that use the Climate Hazards Group Precipitation Climatology (CHPclim) (Funk et al., 2015a) as their backbone and further improve upon it by using rain gauges and streamflow observations as target references to improve performance. Several studies, such as Salles et al. (2019), Wang et al. (2016), and Wang et al. (2019) found good correlation between SPEs and rain gauges in monsoon regions, with the Pearson correlation coefficients (*r*) higher than 0.6. Shige et al. (2015) showed that satellite products combined and calibrated with ground-based rain gauge stations significantly increase the correlation between remote-sensing and observed data. Other studies such as Gilewski & Nawalany (2018) reached *r* values as high as 0.95, and Nash–Sutcliffe Efficiency (NSE) of 0.91, for modeling events with the Hydrologic Engineering Center-Hydrologic Modelling System (HEC-HMS - Scharffenberg & Harris, 2008). These results highlight the potential importance of satellite-based rainfall products.

The SWAT model was selected here for water resource planning in the study area (more on this later). Watershed models provide a reliable approach to water management, especially semi-distributed models, where it is possible to analyze a region based on different aspects such as land use, soils, and spatial rainfall variability (Singh and Frevert, 2006). SWAT is a watershed-scale, process-based, semi-distributed hydrologic model that is being used globally (Gassman et al., 2014), including for monsoon regions (Anand et al., 2018; Hussain et al., 2019; Thapa et al., 2017). Few studies however have utilized SWAT associated with SPEs for streamflow analysis. Singh & Saravanan (2020), using rainfall data from APHRODITE (Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of Water Resources), GPCP (Global Precipitation Climatology Centre), and TRMM in India, obtained NSE values above 0.50 and found that in areas where rain gauges are not evenly distributed, GPCP and TRMM are better suited as sources of rainfall data. Deng *et al*. (2019), using a dataset from GSMaP_Gauge (a GSMaP – Global Satellite Mapping of Precipitation – MVK product, corrected by global gauge data), achieved NSE values from 0.53 to 0.64, and using a correction equation based on local rain gauges, improved these results to the range 0.70-0.75. Duan *et al*. (2019), using datasets from CHIRPS, TRMM, and CFSR (Climate Forecast System Reanalysis) for a watershed in Ethiopia, achieved lower model performance in simulating streamflow compared to input precipitation from sparsely distributed stations (four) across the watershed area (1,656 km^2). However, among those products, CHIRPS produced "good" and "satisfactory" performance for monthly and daily streamflow, respectively, according to the criteria proposed by Moriasi *et al*. (2015). Le *et al*. (2020) evaluated raw SPE and gauge-corrected SPE products from TRMM Multi-satellite Precipitation Analysis (TMPA), PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks), CHIRP, and IMERG (Integrated Multi-satellitE Retrievals for Global Precipitation Measurement) for six watersheds in Vietnam, where gauge-corrected SPE outperformed raw SPE products as well as rain gauges. The NSE values with corrected SPEs varied from 0.47 to 0.63 and 0.56 to 0.69 respectively during the calibration and validation periods where simulation using rain gauges as input yielded NSE values between 0.64-0.69. Corrected IMERG had the best performance among SPE products for streamflow simulations, and CHIRPS exhibited the smallest bias in comparison to rain gauge data. Beck *et al.* (2017) evaluated products from SPEs such as CHIRPS, MSWEP, and others, and modeled 9,053 river basins worldwide. The average NSE was 0.58 and 0.45 for MSWEP and CHIRPS, respectively.

SPE products provide opportunities for understudied regions with sparse rain gauge distribution. Besides some bias challenges, these products can produce satisfactory results. In the Brazilian central plateau, Salles et al. (2019) investigated products from GSMaP, IMERG, and TRMM. Their findings showed that satellite-based rainfall data reached *r* values higher than 0.97 for monthly analysis. On the other hand, they achieved values from 0.51 to 0.83 for annual mean, and values from 0.30 to 0.50 for daily analysis. They suggested that the bias in the results may be due to distribution density and the location of gauges. Beck et al., (2017b) evaluated 23 precipitation datasets using gauge observations and hydrological modeling, and pointed out that MSWEP and Climate CHIRPS achieved good performance.

Past studies mostly analyzed SPE products for much larger watersheds (Beck et al., 2017; Funk et al., 2015). Hydrologic simulations in smaller watersheds are more sensitive to precipitation input (Andréassian et al., 2001; Faurès et al., 1995; McDonnell, 2009) and the potential utility of these products is not well understood for small watersheds (Alnahit et al., 2020). This paper evaluated SPE products using SWAT model simulations in a small Brazilian watershed (112 km²) located in a monsoon region (Gan et al., 2004) with sparse rain gauge distribution. The objectives of this study were: (i) to verify the most appropriate rainfall arrangement for hydrological simulations in a relatively small watershed in central Brazil considering monsoon characteristics, combined and isolated rain gauges as well as the Merged SPE products from CHIRPS and MSWEP; (ii) examine impacts of different precipitation datasets on hydrologic regimes using Indicators of Hydrologic Alterations software (IHA).

6.2. **Materials and Methods**

6.2.1. Study area

The Rodeador watershed, located in the Federal District, on the border of the city of Brasília, (Figure 6-1), was selected as the study site. This watershed is within a monsoon region and is one of the most important regional catchments contributing to the Descoberto Reservoir, responsible for supplying water to 61,5% of the region’s population (GDF, 2017). The watershed area is 112 km² with elevation ranging from 994 to 1356 meters above sea level (SRTM – Shuttle Radar Topography Mission). The land use/cover is mainly comprised of agricultural fields, urban, and forest areas (Table 6-1). The soil is dominated by Latossols (oxisols) and the climate, as in other monsoon regions, is well defined by two seasons. The rainy season is typically from November to April, and the dry season extends from May to October (Figure 6-2), with most rainfall occurring during December, January, and February (Alves et al., 2017). As a result, streamflow reached a minimum value of 0.034 m³/s in the dry season and a maximum value of 27.16 m³/s in the wet season during the studied period (1984-2015). Low flows are more frequent, as supported by daily mean streamflow of 1.46 m³/s (ANA – Agência Nacional de Águas – code 60435200). The watershed area receives approximately 1482 mm of precipitation annually, according to the rainfall register from the two nearest rain gauges (ANA code 01548006 and 01548007) to the catchment. These two gauges were used in this work since there is no rain gauges inside this watershed.

6.2.1. SWAT Model

SWAT is a watershed-scale, continuous-time model known for its robustness as well as its ease of use. It was developed to assess impact of land management practices on water, sediment, and crop yields in watersheds. The model is semi-physically based, semi-distributed, able to capture watershed heterogeneities like varying soil types, slopes, and weather time conditions (Neitsch et al., 2011). SWAT is capable of simulating various water fluxes such as runoff, evapotranspiration, infiltration, percolation, and subsurface flow, as well as many water quality constituents (sediment, nutrients, pesticide, etc.). Additionally, SWAT has been designed to assess hydrological conditions in rural watersheds and has been used worldwide for many years (Gassman et al., 2014).

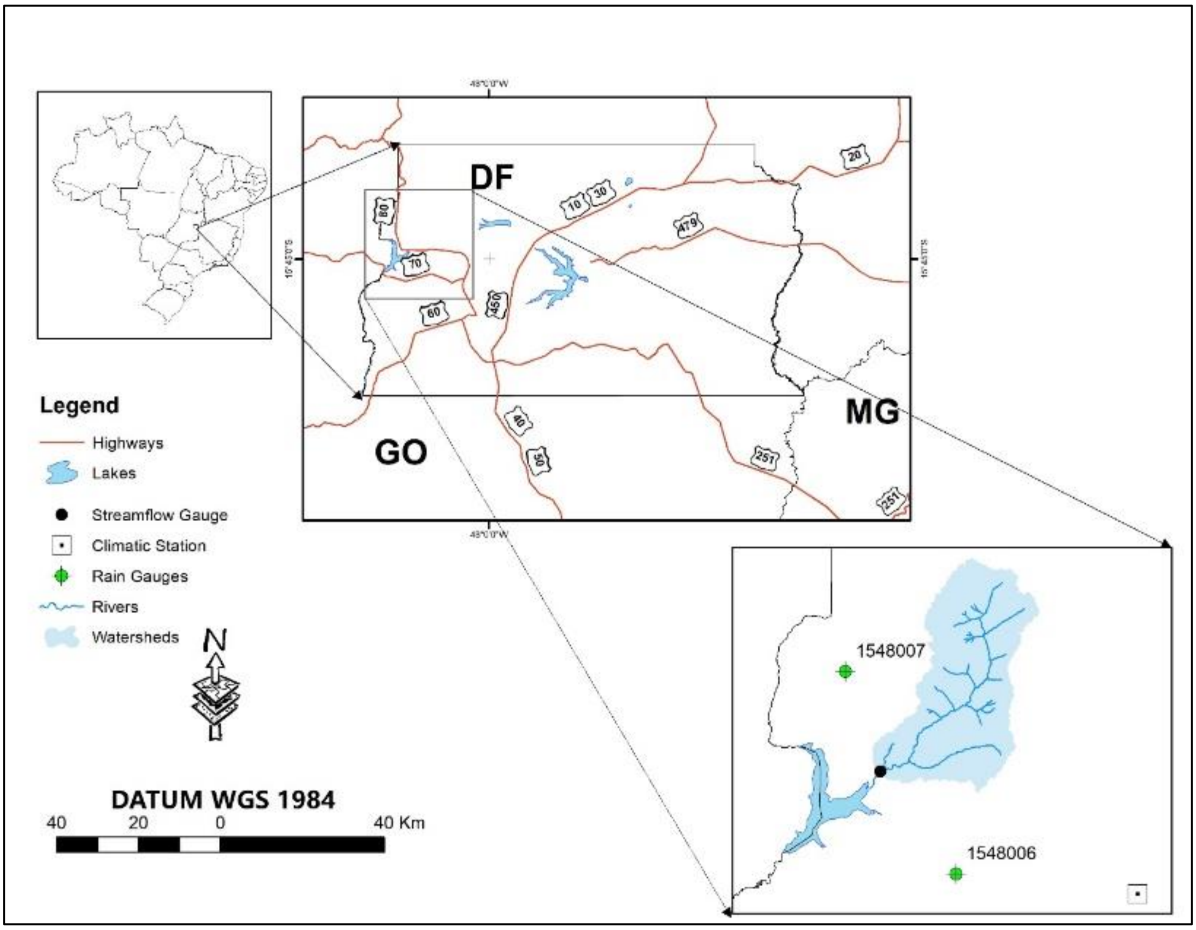

Figure 6-1. Study area

Table 6-1: Land use in percent of watershed area based on IBRAM, 2013

Land use	Percent of watershed
Agricultural	44.60
Urban	18.65
Forestry (Cerrado, Mata and Campo)	32.00
Other land uses	4.75

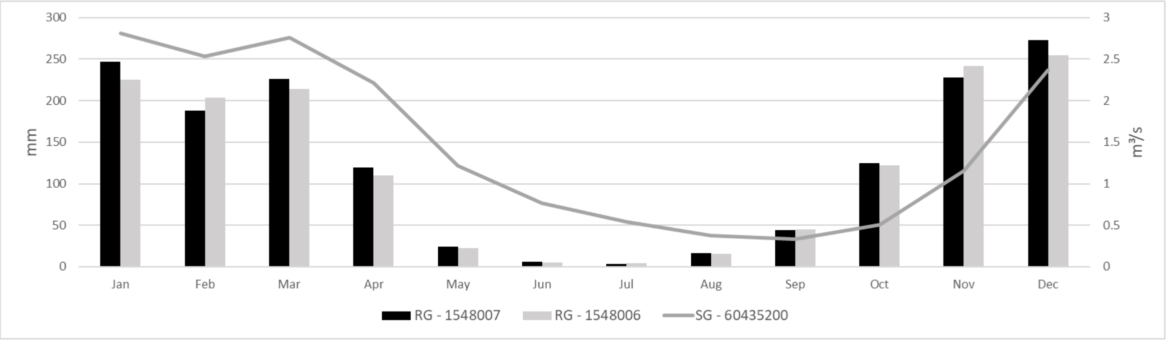

Figure 6-2: Monthly variation in rainfall and streamflow from 1984 to 2015, for two rain gauges (RG) and one streamflow gauge (SG) used in the simulation.

6.2.2. Model setup and input data

The model setup for SWAT 2012 was achieved through ArcSWAT 10.5, an extension of ArcGIS that allows for processing and reading of all model inputs (Table 6-2). The model setup consists of watershed delineation, insertion of climate data, and creation of Hydrologic Response Units (HRUs) based on soil types, land use maps, and digital elevation model (DEM). In SWAT, landscape heterogeneity is represented by dividing the watershed into sub-watersheds, which are further subdivided into unique combinations of slope, land-use, and soil type (Gassman et al., 2007). These unique combinations are known as HRUs and are the smallest computational units in SWAT. Based on the input data described in Table 2, the current study generated 51 subbasins (Figure 6-3a) and 556 HRUs.

6.2.1. Weather data and rainfall limitations

The precipitation data was obtained from two rain gauges located outside the catchment’s boundary (Figure 6-1). The Penman-Monteith method (Monteith, 1965) was used to estimate evapotranspiration. Daily minimum and maximum air temperature, wind speed, relative humidity, and solar radiation data was collected from a national weather station (INMET – Instituto Nacional de Metereologia – National Institute of Meteorology – code 83377), located 27 km from the Rodeador watershed outlet.

Table 6-2: Summary of data used in the SWAT model setup and their sources

Data	Source
Sub-basins (Figure 6-3a)	Generated in ArcSwat 10.5
Land Use/Cover map 30m (Figure 6-3b)	IBRAM, 2013
Digital Elevation Model (DEM) 30m (Figure 6-3c)	Shuttle Radar Topography Mission
Soil Map 1:100.000 (Figure 6-3d)	GDF and SEMA (2012)
Soil property data	Farias et al., (2008); Fiori et al., (2010); Lima et al. (2013); Lima et al., (2014); Reatto et al., (2000); Spera et al., (2005)

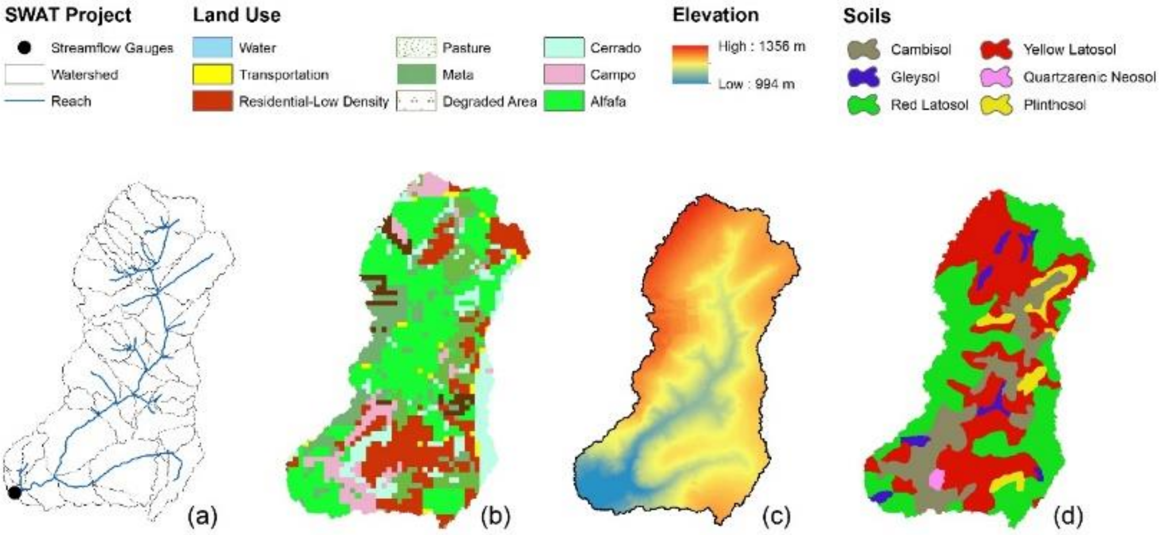

Figure 6-3: Spatial Data used in setting up the SWAT model at the Rodedador Watershed: a) Sub-basins b) Land Use/Cover c) DEM d) Soil Map

The ArcSWAT interface assigns the weather station for each subbasin based on the distance relative to its centroid (Neitsch et al., 2011). In other words, this process does not respect climatic factors and assumes minimal climate variability across the study area. However, when precipitation data is analyzed for our study site, one can observe considerable variability across the watershed area. ArcSWAT assigned rainfall data to the Northern subbasins based on rain gauge 1548007 (WEST), while other subbasins were assigned data from the rain gauge 1548006 (EAST). Considering the convective characteristics of rainfall in this region, the default method used by ArcSWAT to assign weather stations based solely on geographic distance may be a limiting factor. Because of that, in addition to the lack of ground-based weather stations within the catchment area, here we explore the benefits and drawbacks of using Merged SPE products and different configurations of rain gauges, analyzing impacts throughout the model. Interpolation is a possibility for improving hydrologic performance (Masih et al., 2011; Strauch et al., 2012), however, since the area has just 2 stations, we opted to use the simple arithmetic average as interpolated data representing one rainfall input dataset (90% of the basin is assigned to one station). Another approach is using SPE data as virtual stations in SWAT simulations (Deng et al., 2019; Zou et al., 2016) (Figure 6-4). The selected approaches and datasets are briefly described below and the SPE specifications are detailed in Table 6-3.

I) Rain gauge assignments proposed by the ArcSWAT algorithm, where rain gauge 1548007 was assigned to the northern subbasins, whilst rain gauge 1548006 was assigned to the southern subbasins, namely NORMAL.

II) Only rain gauge 1548007 was used for all the subbasins and spatially uniform rainfall is assumed across the entire watershed, namely WEST.

III) Only rain gauge 1548006 was used for all the subbasins and spatially uniform rainfall was assumed across the entire watershed, namely EAST.

IV) Simple arithmetic average of stations 1548007 and 1548006 was used as one station for all the subbasins, namely AVG.

V) MSWEP version 2 gridded data was used as precipitation forcing. We created 12 virtual stations in ArcSWAT, one for each MSWEP grid (0.1°) falling within or intersecting the watershed boundary. Using this approach, the ArcSWAT algorithm (the default procedure) selected 6 out of the 12 inserted stations, which were distributed across 51 subbasins, namely MSWEP. The MSWEP data was aggregated daily.

VI) CHIRPS gridded data (0.05°) was used as precipitation forcing. We created 51 virtual stations, one for each subbasin’s centroid, namely CHIRPS.

Table 6-3: Specifications about the P Dataset used in this study

Source	Spatial resolution	Temporal resolution	Temporal coverage
MSWEP	0.1°	3 hourly	1979 – 2015
CHIRPS	0.05°	Daily	1981 – Present

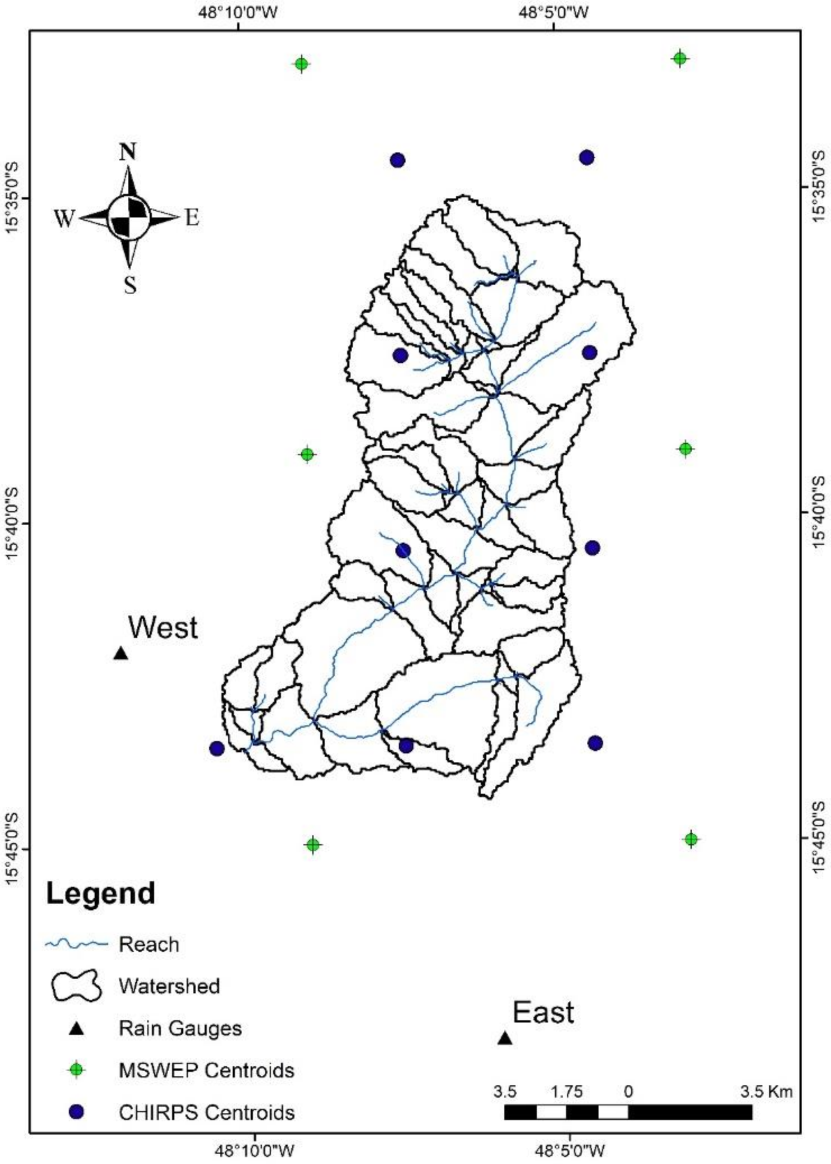

Figure 6-4: Study area and spatial distribution of the selected precipitation data

6.2.2. Methodology to assess the SPE products

The assessment of SPE products was carried out using four statistical methods: Probability of Detection (*POD*), the False Alarm Ratio (*FAR*), the Critical Success Index (*CSI*), and the Bias (*BIAS*) (AghaKouchak and Mehran, 2013; Le et al., 2020; Salles et al., 2019; Satgé et al., 2017) (Equations 1-4). These statistics are based on three variables that represent the number of rain events (base on the following thresholds: 0.5, 1, 2, 5, and 10 mm daily rainfall) detected by variable a → both ground-based gauge and virtual gauge (SPE grid); variable b → only the SPE product; variable c → only the ground-based gauges. *POD* indicates capacity of detection of actual events, varying from 0 to 1, where 1 is the best value. *FAR* verifies false events and ranges from 0 to 1, where 0 is the best value. *FAR* can also be represented as Success Ratio (SR), where SR = 1 – *FAR*. *CSI* is defined as the ratio of rain events correctly detected by SPEs and the sum of events observed in both sources (ground-based and virtual). *CSI* varies from 0 to 1, with the best value being 1. *BIAS* is the ratio of SPEs related to actual precipitation events, where values higher than 1 signify overestimation, and lower than 1 indicate underestimation.

$$POD = \frac{a}{(a+c)} \tag{1}$$

$$FAR = \frac{\mathrm{b}}{(a+b)} \tag{2}$$

$$CSI = \frac{a}{(a+b+c)} \tag{3}$$

$$BIAS = \frac{(a+\mathrm{b})}{(a+c)} \tag{4}$$

To better understand their performance for small events, we tried different rainfall thresholds: 0.5, 1, 2, 5, and 10 (mm). Each method was tested to identify degree of detection for an expected rainfall amount represented by the specified threshold.

For comparison purposes, as we have two different pixel resolutions (i.e., 0.1° and 0.05°), two approaches were chosen to analyze SPE products: i) For CHIRPS, each ground-based gauge was related to the nearest grid centroid (virtual gauge); ii) For MSWEP, as both physical rain gauges were located between two virtual centroids

(Figure 6-4), the average for each group of two centroids was estimated. As a final result, we calculated the average of each statistic related to SPEs.

Other statistical analyses such as standard deviation (STD), correlation coefficient (CC), and centered root mean square (RMSEc) were used to compare overall performance. These indexes were described using the Taylor Diagram (Gleckler et al., 2008; Taylor, 2001). As Jolliff et al. (2009) suggested, the Taylor Diagram provides comprehensive information about model performance taking advantage of well-known statistical quantities.

6.2.3. Evaluation of SWAT performance

In order to quantify the model performance in predicting daily streamflow based on different approaches for generating precipitation input data, the simulation period was split into calibration (1981-1999) and validation (2000-2015) periods, including a warm-up period of three years. The models were calibrated and validated using the SWAT Calibration and Uncertainty Program (Abbaspour, 2015 - SWAT-CUP), and the Sequential Uncertainty Fitting (SUFI-2) algorithm (Abbaspour, 2015) was used to generate values for 28 SWAT parameters related to streamflow generation and routing. The initial ranges for these parameters were derived from published literature (Farias et al., 2008; Fiori et al., 2010; Lima et al., 2013; Maia et al., 2018; Reatto et al., 2000; Spera et al., 2005; Strauch and Volk, 2013), and the statistical measures used to evaluate the model performance were (NSE), coefficient of determination (R^2), and percent bias (PBIAS), based on guidelines proposed by Moriasi et al. (2015). Five iterations were performed with 500 simulations for each one and executed for every type of approach (Abbaspour, 2015). The AVG approach was an exception since a significant improvement was not observed for the fifth iteration, and the other approaches did not show improvement after the fifth iteration. After each iteration, new parameter values suggested by SWAT Cup were analyzed in order to avoid unrealistic values and adequated for real ranges as necessary.

In addition to these statistical measures, this study employed an ecological analysis based on the Indicators of Hydrologic Alterations (IHA) software (Richter et al., 1996). This tool calculates the characteristics of natural and altered hydrologic regimes based on a long-term daily streamflow record, indicating the degree of hydrologic alteration within an ecosystem (Richter et al., 1996) and its effects on the biota (Richter et al., 1997). This easy-to-use tool allows for comparison of hydrological behavior during different periods and/or under different conditions (e.g., hydrologic data from different models), investigating trends and suitability of models (Dosdogru et al., 2020; Mathews and Richter, 2007). The ecologically relevant hydrologic parameters used in this study can be divided into 5 groups, totaling 39 parameters, as summarized in Table 6-4:

Table 6-4: Summary of hydrological parameters used in the IHA to characterize flow regime and their ecosystem influences (Dosdogru et al., 2020; TNC, 2009)

IHA Parameter Group	Hydrologic Parameter
Magnitude of monthly water condition (12 parameters)	Median value for each calendar month
Magnitude and duration of annual extreme water conditions (11 parameters)	Annual minima/maxima, 1-day mean Annual minima/maxima, 3-day means Annual minima/maxima, 7-day means Annual minima/maxima, 30-day means Annual minima/maxima, 90-day means Baseflow index: 7-day minimum flow/mean flow for the year
Timing of annual extreme water conditions (2 parameters)	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum
Rate and frequency of water condition changes (2 parameters)	Rise rates: median of all positive differences between consecutive daily values Fall rates: median of all negative differences between consecutive daily values
Environmental Flow Components (EFCs) Parameters – Monthly low flows (12 parameters)	Mean values of low flows during each calendar month

The IHA parameters are aimed at understanding the hydrologic regime over a certain period. Ecosystem influences such as habitat availability for aquatic organisms, soil moisture for plants, reliability of water supplies for terrestrial animals, and other aspects can be analyzed based on long periods of daily hydrologic data (Richter *et al*., 1996). In the current study, as we are exploring scenarios using different approaches for precipitation input data, the goal was to verify rainfall datasets that are more suitable from an ecological perspective. For more information about IHA parameters, readers are referred to the IHA user manual (TNC, 2009), as well as the software's scientific basis described in Richter *et al*. (1996). Initially, observed streamflow measured at the watershed outlet, and SWAT generated daily streamflow that were fed into the IHA software and the Shapiro-Wilk test (Shapiro and Wilk, 1965) was applied to verify normality of the data (Yap and Sim, 2011). Next, the Kruskal–Wallis test (Kruskal and Wallis, 1952) followed by Dunn's test (Dunn, 1961) was applied to the IHA outputs in order to investigate differences and similarities between ecologically relevant parameters calculated based on SWAT generated streamflow from different rainfall input, and observed streamflow data. The Kruskal–Wallis test is a nonparametric method used to compare many groups and test the null hypothesis that the samples are from identical populations (Hecke, 2012). The Dunn's test is a multiple nonparametric comparison test for pairwise comparisons and is used to verify what group from *n* groups belong to a different distribution after the Kruskal–Wallis null hypothesis has been rejected (Dinno, 2015). Finally, the relative percentage difference between IHA parameters generated from SWAT streamflow outputs and observed streamflow data was calculated and compared.

6.3. Results

6.3.1. Assessment of SPE products

The results of the comparison of precipitation data from SPE products and rain gauges are shown in figures Figure 6-5 and Figure 6-6. The statistical analyses shown in Figure 6-5 illustrates performance for CHIRPS and MSWEP under different thresholds, based on *POD*, *FAR*, *CSI*, and *BIAS*. Except for *BIAS*, both SPE products showed similar trending for all analyses. However, for extremely low rainfall values (0.5 mm/day), MSWEP demonstrated better performance than CHIRPS, achieving a *POD* value of 0.73, higher than the 0.59 achieved by CHIRPS (Figure 6-5a). Although both SPE's demonstrated lower performance at higher thresholds (10 mm/day), with values below 0.5 and 0.3 for *POD* and *CSI*, respectively, CHIRPS outperformed

MSWEP overall. As explained in section 2.4, *POD* represents the capacity of the detection of actual rainfall events. *CSI* represents SPE limitation in identifying rainfall events and/or assessing false events (Figure 6-5c). As *POD* performed better than *CSI*, it can be inferred that SPEs tend to estimate false rainfall events. This can be visualized in the *FAR* analysis, where SPEs reached a success ratio (1 – *FAR*) over 0.6 for 0.5 mm/day, and approximately 0.4 for 10 mm/day (Figure 6-5b). As the threshold increases, it becomes easier to observe false events. The BIAS graph (Figure 6-5d) demonstrates that SPEs can behave differently for the same period - during very light rain events (e.g., 0.5 mm/day) (WMO, 2012). CHIRPS tends to underestimate rainfall, while MSWEP, capable of observing light drizzles, tends to overestimate it. The opposite is observed during moderate rainfall events (10 mm/day) (WMO, 2012).

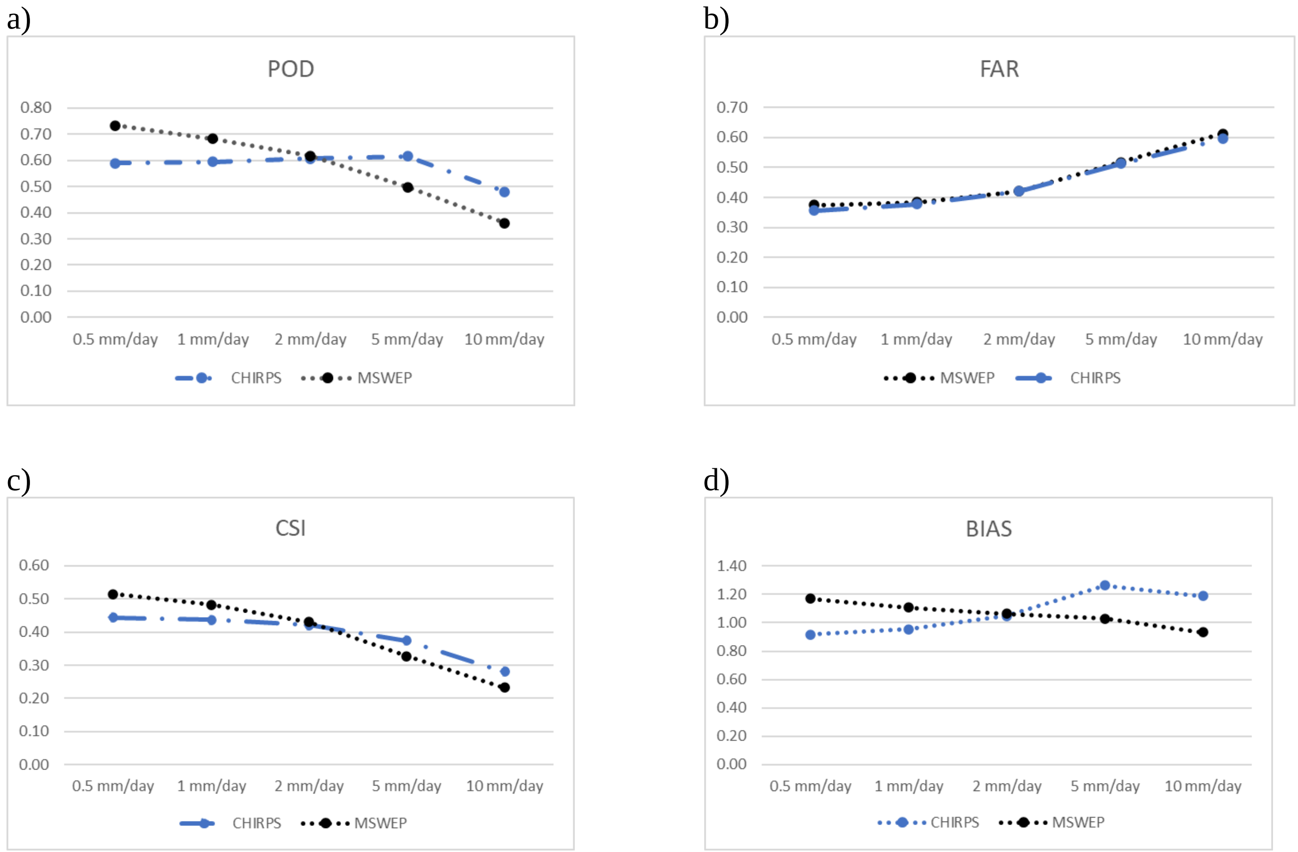

Figure 6-5: Statistical analysis based on different thresholds (from 0.5 mm/day to 10 mm/day) . a) *POD*, b) *FAR*, c) *CSI*, d) *BIAS*.

a) b)

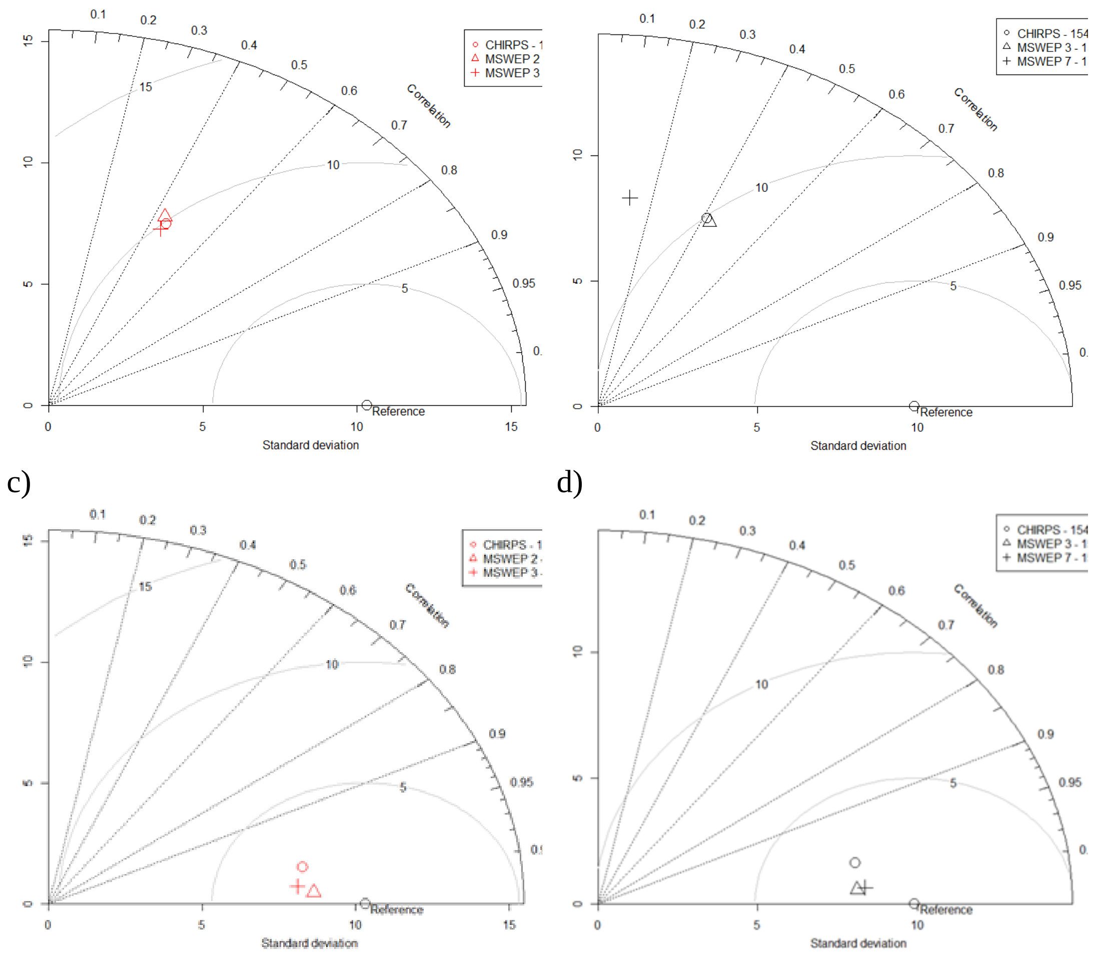

Figure 6-6: Taylor Diagram for daily events based on rain gauge: a) 1548007; b) 1548006; c) 1548007 using flow duration curve; d) 1548006 using flow duration curve;

The Taylor diagrams for daily events (Figure 6-6 a and b) show low performance in correlation between SPEs and rain gauges for all events throughout the entire simulation period. The correlation for most of SPEs was approximately 0.4, and the RMSEc is 10 mm. However, the *STD* value for SPEs was lower than referenced, with values below 10 mm. In contrast, the Taylor diagrams for exceedance curves depicted in Figure 6-6 (c and d) show good performance (correlation over 0.95), which demonstrates that overall rainfall events captured by SPEs tend to be similar to what is recorded by the ground-based rain gauges.

6.3.2. Streamflow calibration and validation performance

The model performance in simulating daily streamflow using different precipitation inputs is summarized in Table 4 in terms of R^2, *NSE*, and *PBIAS*. According to Moriasi et al. (2015), the best results were achieved using the arithmetic average (AVG) and CHIRPS rainfall inputs. For these sources of precipitation, the model performance can be classified as satisfactory in terms of R^2 and *NSE*. In terms of PBIAS, model performance falls into the very good and good categories, for AVG and CHIRPS, respectively, during the calibration period. Except for the WEST input (station number 1548007), all rainfall datasets performed satisfactorily based on NSE, and good to very good based on R^2, during the same period. For the validation period, CHIRPS yielded the best R^2 among all input datasets. When analyzing NSE, except for EAST and West inputs, all rainfall inputs resulted in satisfactory performance. Regarding *PBIAS*, the only good performance was obtained by CHIRPS, whilst the other input datasets fell into the satisfactory category. Overall, the model performance using CHIRPS data was equal or better than satisfactory during both the calibration and validation periods. Figure 6-7 exhibits comparisons between observed streamflows (black dots) and simulated streamflows for different rainfall inputs.

Table 6-5: Summary of model performances at a daily level for all rainfall input. R^2, NSE, PBIAS, and NSE for Flow Duration Curve (FDC) correspond to the parameter set with the best model performance based on NSE.

	Calibration (1984-1999)				Validation (2000-2015)			
Input	R2	NSE	Pbias	NSE (FDC)	R2	NSE	Pbias	NSE (FDC)
Normal	0.56	0.53	2.0	0.98	0.54	0.50	10.2	0.98
AVG	0.63	0.62	0.0	0.95	0.57	0.56	11.0	0.95
East	0.57	0.56	6.0	0.94	0.48	0.45	14.5	0.90
West	0.50	0.43	0.5	0.98	0.49	0.43	12.5	0.97
CHIRPS	0.62	0.59	7.2	0.97	0.61	0.57	8.0	0.98
MSWEP	0.57	0.55	8.9	0.96	0.56	0.52	11.6	0.96

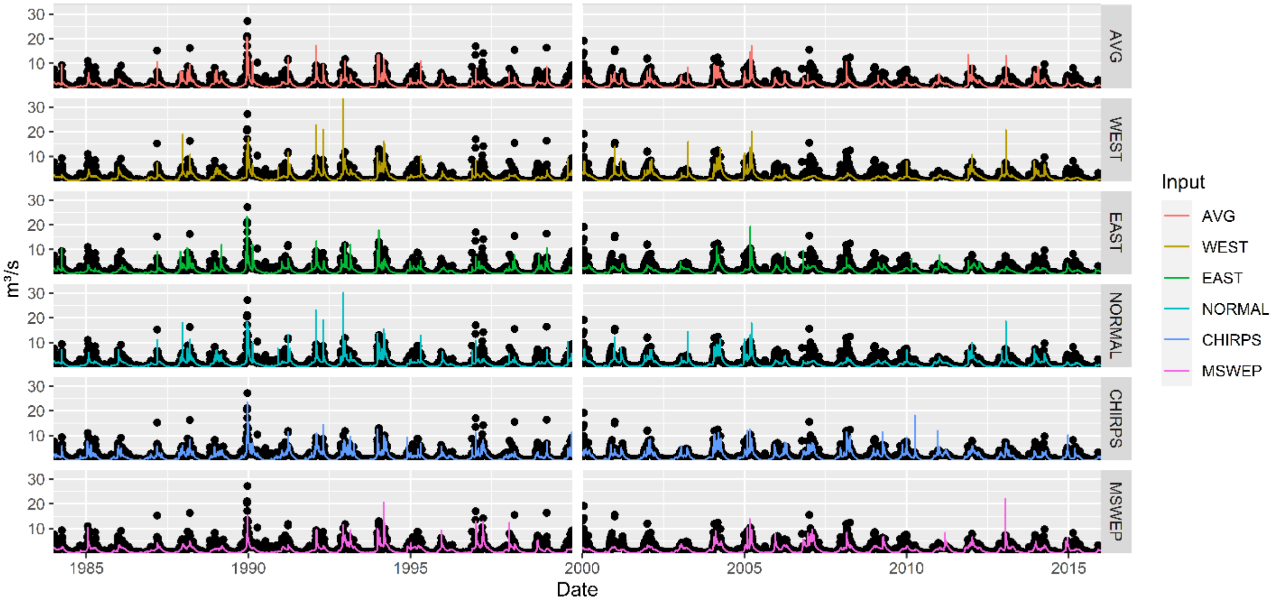

Figure 6-7. Comparisons between observed and simulated streamflows (black dots) for different rainfall inputs.

6.3.3. IHA Analyses

The IHA analyses were carried out for the entire simulation period (1984-2015) and each of the rainfall inputs used in the current study. Each IHA group was examined separately by comparing observed streamflows to simulated streamflows for each rainfall input. Figure 6-8 describes the first IHA group, which represents the magnitude of the median monthly flows. The dashed line represents no variation between the simulated median streamflows and the observed median streamflows and is used as a reference in Figures Figure 6-8 through Figure 6-12. In general, all models presented similar behavior in terms of median monthly streamflow, however, CHIRPS and MSWEP showed significant negative variation during the dry season, indicating underestimation for this period. The WEST input performed best in replicating median monthly streamflow for the dry season. During the wet season, except for November, which is the first month of the hydrological year, CHIRPS and MSWEP performed slightly better than other inputs. Table 6-6 describes the relative deviation in median variations for the analyzed period (1984-2015), considering all IHA parameters. CHIRPS, followed by MSWEP, presented the highest differences from March to December. Additionally, WEST input shows the lowest difference for 4 months, including 3 from the dry season. The Dunn’s test at the 5% significance level was applied for pairwise comparisons between observed and SWAT generated streamflow for all rainfall inputs for each month. Based on our findings, CHIRPS and MSWEP were rejected for June, and it was accepted that both precipitation datasets had the same distribution. All inputs were rejected for July and August and CHIRPS was the only input rejected in September. MSWEP was accepted having the same distribution as CHIRPS and OBS.

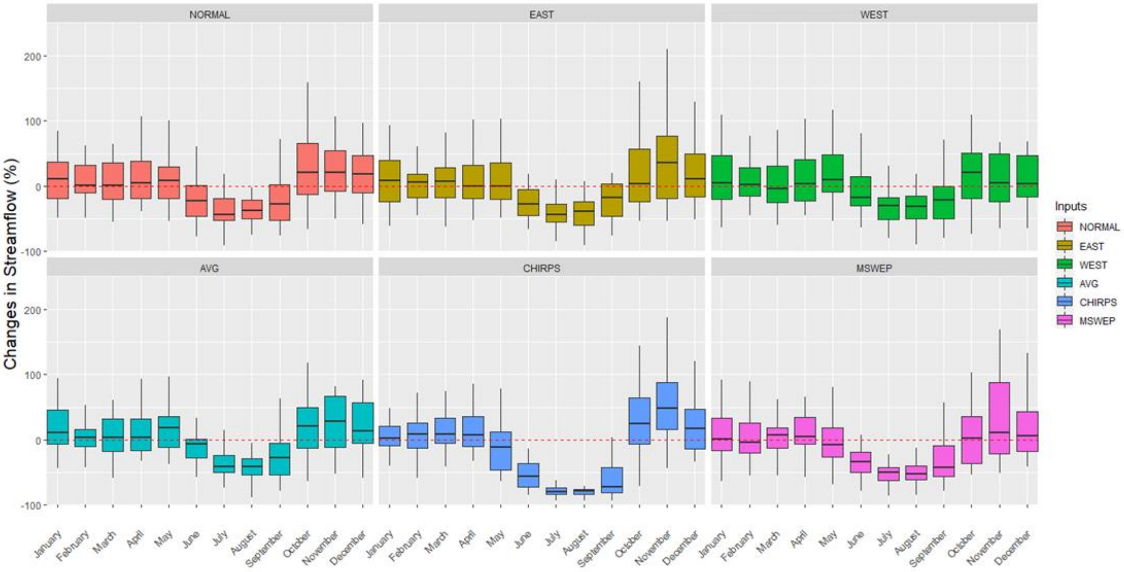

Figure 6-8: Relative changes in median value for each calendar month. A few outliers were omitted from the figures for clarity.

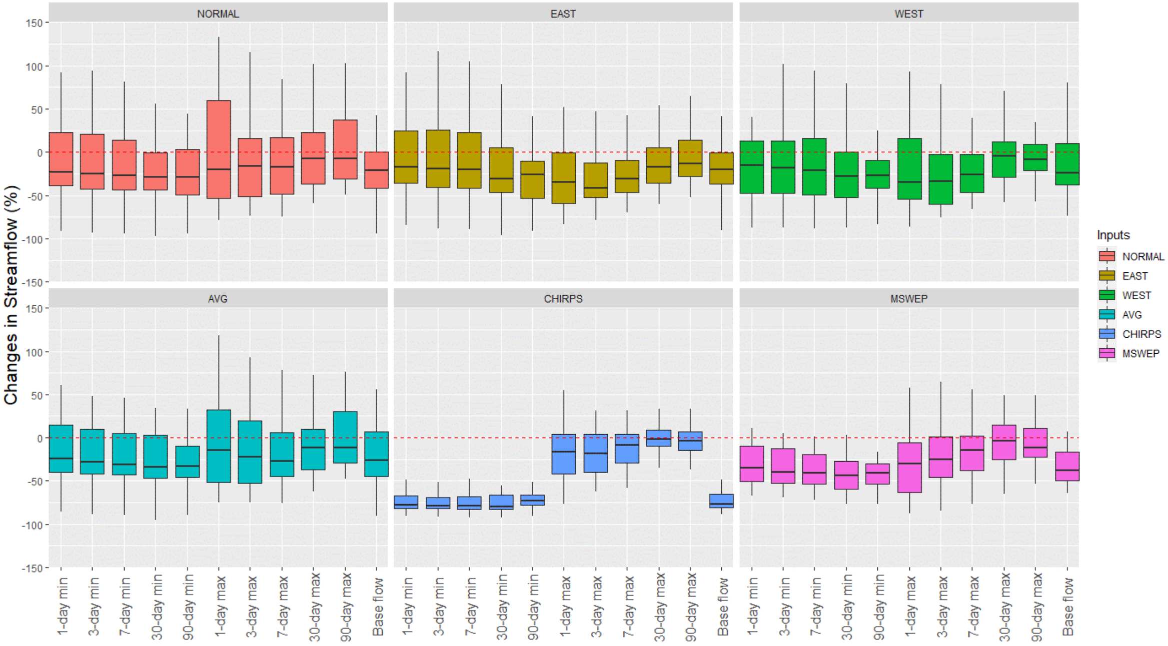

Figure 6-9: Relative changes in annual extreme streamflow

Figure 6-9 illustrates the second IHA group, which consists of minimum and maximum mean peaks for days 1, 3, 7, 30, and 90. The minimum values showed in

Figure 6-9 indicate underestimation from SPEs during events that occurred in the dry season, especially with CHIRPS. For the same events, the smallest dispersion was observed for the AVG input, where median values nearest to zero were produced by the WEST Input. In contrast, for the maximum values, the smallest dispersion was reached by CHIRPS. MSWEP did not produce significant improvements for minimum and maximum values but maintained low dispersion for all items in this IHA group. In Table 6-6 similar results can be observed, where CHIRPS yielded the highest differences for the minimum parameters, as well as for baseflow. However, CHIRPS produced the lowest deviations at 7, 30, 90-day max. As expected, the Dunn's test rejected CHIRPS for all minimum parameters as well as differences for all rainfall inputs related to maximum flow parameters. Also, in Table 6-6, it can be observed that MSWEP did not produce better results compared to rain gauge inputs (WEST, EAST, NORMAL, and AVG) for most of the IHA variables, with the exception of some months for baseflow. Dunn's test identified MSWEP as presenting the same distribution as rain gauge inputs with the exception for June lowf and September lowf.

The third IHA group helps to understand if extreme flow events (minimum or maximum) happen earlier (negative values) or later (positive values) for different rainfall inputs.

Figure 6-10 shows that the WEST input data produced the smallest dispersion of temporal variability for minimum and maximum flows. In general, for Date min, all inputs had similar behavior. However, for the Date max, WEST, followed by MSWEP and CHIRPS, performed best. Interestingly, WEST showed the lowest deviation (later) for the mean minimum peak, while CHIRPS showed the highest deviation for the same parameters (Table 6-6). Both inputs had opposite behavior concerning Date max, where CHIRPS had 1.09 mean delay day. Dunn's test rejected the hypothesis that all rainfall inputs are different from each other.

Table 6-6: Percent deviation of simulated IHA metrics for different rainfall sources from the IHA metrics calculated from observed streamflow

IHA group	NORMAL	EAST	WEST	AVG	CHIRPS	MSWEP
Magnitude of monthly water conditions						
Mean flow in January	4.18	-1.46	3.08	2.27	0.37	4.20
Mean flow February	5.85	0.30	7.92	0.08	7.35	0.04
Mean flow in March	4.95	5.61	5.34	1.86	11.61	3.18
Mean flow in April	5.61	1.98	8.27	4.54	11.76	5.23
Mean flow in May	5.04	-0.26	14.71	9.15	-14.96	-5.91
Mean flow in June	-20.87	-28.19	-11.10	-12.55	-53.61	-32.52
Mean flow in July	-39.99	-43.03	-34.34	-38.65	-78.65	-51.34
Mean flow in August	-39.41	-40.18	-34.39	-43.36	-79.28	-53.25
Mean flow in September	-23.41	-19.48	-25.48	-25.38	-54.66	-29.94
Mean flow in October	15.86	12.33	10.72	13.13	29.00	4.98
Mean flow in November	9.37	16.00	-1.99	11.30	29.71	10.92
Mean flow in December	2.06	-3.92	-5.89	4.67	6.90	2.93
Magnitude and duration of annual extremes water conditions						
1-day min	-27.99	-28.00	-25.89	-31.56	-75.29	-42.36
3-day min	-29.05	-29.08	-27.04	-32.61	-75.64	-43.43
7-day min	-30.25	-30.47	-28.37	-33.94	-75.97	-44.77
30-day min	-33.64	-33.97	-32.24	-37.83	-76.41	-47.96
90-day min	-31.36	-31.85	-28.70	-33.27	-70.62	-45.20
1-day max	-11.55	-30.92	-12.76	-20.48	-20.67	-33.49
3-day max	-20.15	-35.60	-23.08	-25.60	-20.47	-27.14
7-day max	-15.53	-26.60	-17.55	-19.37	-11.81	-16.43
30-day max	-9.50	-14.86	-8.28	-13.13	-4.57	-7.64
90-day max	-5.49	-9.65	-4.69	-9.15	-1.42	-7.09
Base flow	-28.13	-24.62	-26.22	-30.63	-74.13	-38.29
Timing of annual extremes water conditions						
Date min	-17.31	-13.66	-12.63	-22.41	-22.72	-22.50
Date max	5.16	6.84	7.50	4.34	1.09	-4.59
Rate and frequency of water condition changes						
Rise rate	-78.34	-77.78	-80.66	-83.16	-42.34	-79.63
Fall rate	-78.63	-79.41	-79.50	-78.91	-68.00	-78.75
EFCs Parameters – Monthly low flows						
Jan lowf	28.67	26.59	20.50	32.95	17.57	15.00
Feb lowf	26.55	19.50	23.25	30.44	15.86	15.28
Mar lowf	6.18	14.67	1.47	7.26	10.11	6.10
Apr lowf	11.00	10.07	5.50	14.42	2.63	2.44
May lowf	9.28	6.88	14.28	15.50	-14.72	-6.00
June lowf	-17.00	-21.66	-8.31	-8.28	-54.41	-31.72
July lowf	-35.90	-39.21	-31.43	-36.81	-76.83	-48.63
Aug lowf	-29.27	-33.38	-24.96	-35.58	-73.15	-48.24
Sept lowf	-16.87	-13.13	-13.59	-17.68	-44.12	-29.83
Oct lowf	12.97	13.03	10.60	11.62	16.60	-5.60
Nov lowf	25.94	34.65	8.03	28.59	48.41	25.63
Dec lowf	42.70	38.22	35.87	42.88	49.26	44.28

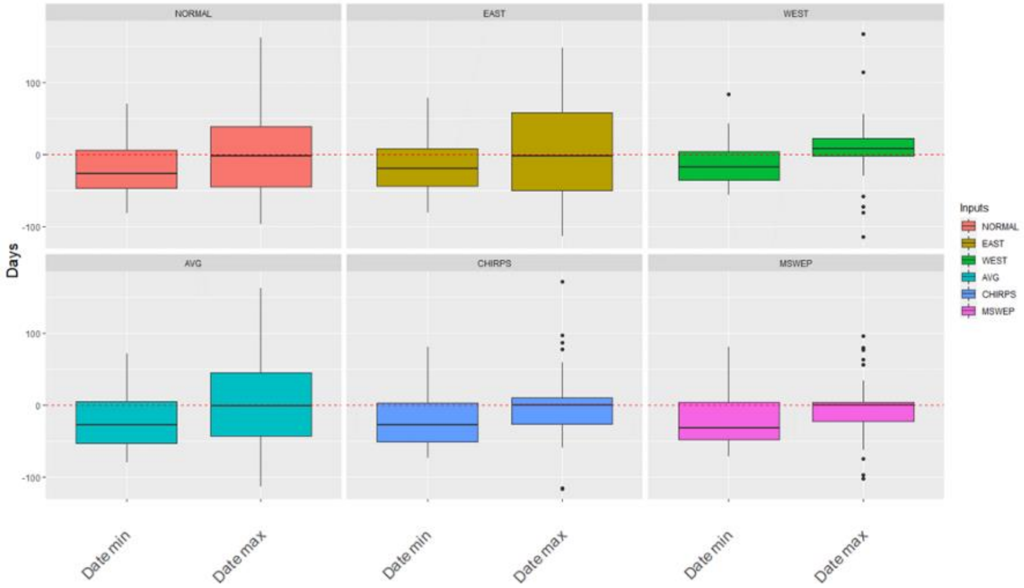

Figure 6-10: Julian date of each annual 1-day maximum/minimum

The rate and frequency of streamflow, represented by the fourth IHA group showed here, describes the median of all positive/negative differences between consecutive daily values. This is represented by Figure 6-11, which shows that all rainfall inputs produced underestimation when compared to observed streamflows. CHIRPS registered the lowest deviation for Rise and Fall rates, as shown in Table 6-6. Dunn's test applied for this group returned the same results as the previous. However, CHIRPS was also considered different from other input datasets, as is presented in Figure 6-11 and Table 6-6.

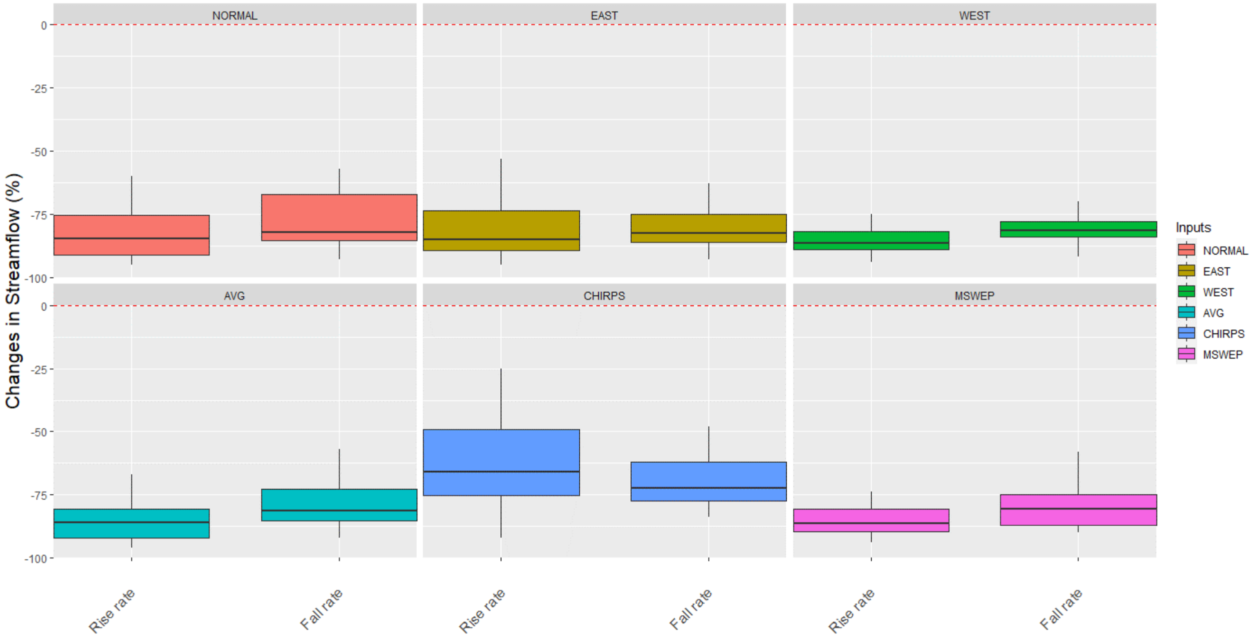

Figure 6-11: Changes in rate and frequency of streamflow

The last group of IHA parameters is depicted in Figure 6-12. These parameters represent the median values of low flows during each calendar month. CHIRPS presented the highest deviation during the dry season, as can be seen in the monthly medians illustrated in Figure 6-8, and similar behavior is described in

Figure 6-9. The WEST input dataset, followed by the SPEs, generated good model performance during the wet season, minus the first two wet months (November and December). Table 6-6 describes the same behavior for monthly low flows and shows that CHIRPS and WEST presented the highest and lowest differences, respectively. In line with this finding, from May to September, all inputs were rejected by the Dunn’s test when compared with observed streamflows.

6.4. **Discussion**

Analyzing Table 6-5, it is possible to see that CHIRPS, followed by AVG, yielded better results than other rainfall inputs. Similar findings were also reported by studies such as Tuo *et al.* (2016) for three watersheds in Italy (areas of 408 km², 259 km², and 338 km²). Conversely, Duan et al. (2019) modeled a 1,656 km² watershed using CHIRPS and four gauges as rainfall input, and achieved the best model performance using in-situ stations. However, in their study, CHIRPS is still considered “good” and “satisfactory” for monthly and daily inputs respectively, according to Moriasi *et al*. (2015). Other studies have observed similar performance for CHIRPS and rain gauge inputs (Zeiger and Hubbart, 2017), as well as for MSWEP and rain gauges (Tang et al., 2019). Higher elevations and watershed size, as highlighted in Duan et al., (2019), should be considered in watershed modeling studies using CHIRPS as input data, since this dataset is particularly appropriate for relatively flat and small-scale watersheds (Duan et al., 2016; Le and Pricope, 2017).

The statistical analyses related to capacity of rain detection (POD, FAR, CSI and PBIAS - Figure 6-5) and the Taylor diagrams (Figure 6-6 a and b) help to understand that the best performance of SPEs occurs during the wet season. This finding is supported by Duan *et al*. (2016), where SPEs tended to present more errors in the dry months of their study. They also verified poor correlation between CHIRPS and rain gauges for daily recording, based on R^2 values, POD, and CSI (0.11, 0.23, and 0.22, respectively), for a 12,000 km² watershed in Italy. Conversely, Tang *et al.* (2019) obtained values of 0.91, 0.03, and 0.88 for POD, FAR and CSI, respectively, in a 795,000 km² watershed located in southeast Asia (China, Laos, Myanmar, Thailand, Vietnam, and Cambodia), utilizing approximately 82 rain gauges. This despite the elevation of this watershed varying from 5 to 5589 m, and with most of the gauges (68) located between 5 and 1000 meters above sea level. Alijanian *et al.* (2017) found similar results in Iran. The authors achieved coefficient of correlation of 0.72 for the entire country, and good performance for POD, FAR, and CSI (0.87, 0.04, 0.84, respectively) for rainfall events less than 1 mm/day. However, as the threshold increased the performance deteriorated, reaching values as low as 0.37, 0.74, and 0.18 for precipitation events ≥ 1 mm/day and < 5 mm/day. Figure 6-5 also suggests lower correlation for SPEs when considering rainfall events greater than 5 mm/day. Figure 6-6 c and d, which are based on the FDC, show good correlation for both SPEs products. Similar results were achieved by Ullah *et al.* (2019). The authors demonstrated that CHIRPS and MSWEP were able to capture extreme precipitation events in Pakistan when they analyzed FDCs.

Table 6-6 shows a more detailed hydrological analysis. It is clear that for different seasons and months, each rainfall input generates different performance. Overall, SPEs performed poorly during the dry season but showed good results in the wet season. Figure 6-9 may help to explain this. SPEs produced satisfactory results for maximum flows, while the opposite trend was observed for minimum flows. Further, Figure 6-10 also shows that SPEs did not produce good results for 1-day maximum flows. As reported by others, SPEs tend to underestimate streamflows (Beck et al., 2017a, 2017b), especially for daily comparisons (Beck et al., 2017b). However, for multi-day or longer duration averages, SPEs presented advantages over ground-based stations. During the dry season, the underestimation exhibited by SPE data was more evident, and consequently the IHA outputs deteriorated in comparison to the wet season. Our results are in line with the findings of Shen *et al.* (2010), who analyzed other SPEs in China and verified better agreements in the wet season over the dry regions.

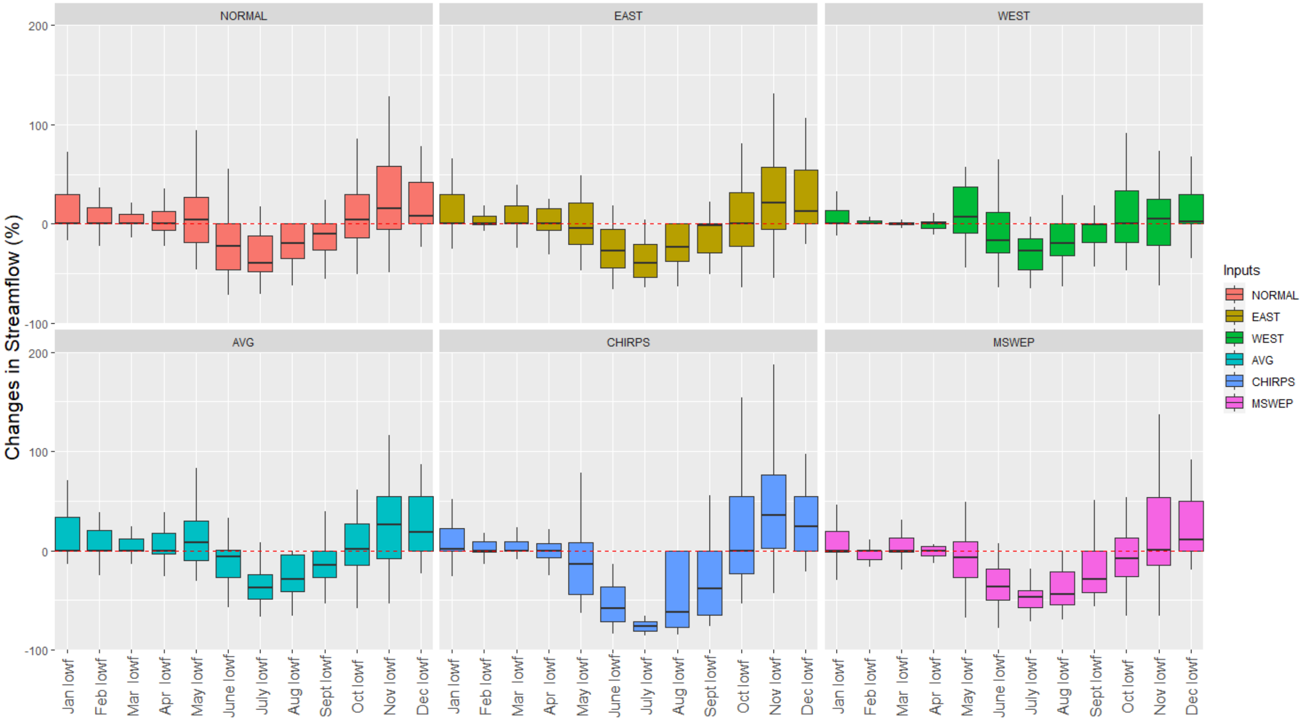

Figure 6-12: Changes in monthly low flows

6.5. **Conclusions**

This study evaluated performance of the SWAT model using different configurations and datasets for rainfall input data. We assessed model performance in forecasting daily streamflow using data from traditional rain gauges and SPEs from CHIRPS and MSWEP. Precipitation from rain gauges was split into 4 datasets: the default procedure in SWAT for selecting source rainfall data based on centroid distances (NORMAL); taking just Eastern gauges input (EAST); the same procedure for the Western gauge (WEST); and use of the arithmetic average of both gauges (AVG). Based on the results of this study, the following conclusions were drawn:

- CHIRPS achieved “satisfactory” performance, based on NSE, R^2, and PBIAS index, during the calibration and validation periods.

- MSWEP was classified as “satisfactory” based on NSE and PBIAS during the calibration period, and “satisfactory” (NSE) and “very good” (PBIAS) for the validation period. The R^2 was “unsatisfactory” for both periods (calibration and validation).

- SWAT performance was best when arithmetic average (AVG) was used for rain gauge data only, obtaining “satisfactory” performance for the three utilized indexes in both periods, except R^2 during the validation period. The other configurations (EAST, WEST, etc.) presented some difficulties in achieving good agreement in the R^2 index, and showed lower performances for validation.
- IHA was important in allowing for analyses of other implications of hydrological modeling, which can be masked or ignored using only the traditional index (NSE, R^2, and PBIAS). The capacity to better understand input for different months/seasons was important to support ideal rainfall input for future projects in the studied area. CHIRPS was considered the best choice for wet months, while WEST presented good behavior throughout the year.

This study shows that SPEs can significantly improve modeling, especially for ungauged areas, as well as for different rainfall configurations. Depending on the characteristics of a region, and on the study’s needs, a particular rainfall source may be more suitable. For instance, our study, aimed at assessing low flows should consider using precipitation data from the WEST rain gauge. Conversely, if the interest was in modeling high flows, CHIRPS should be considered as a more adequate rainfall input.

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7. A NEW APPROACH TO OVERCOME LIMITATIONS OF CN PARAMETER AND BASEFLOW IN THE SWAT MODELS APPLIED TO MONSOON REGIONS

7.1. Introduction

Monsoon climate can be characterized by a strong contrast between rainy summer weather and dry winters (Webster, 1987). Significant seasonal variation in circulation and rainfall between summer and winter is a fundamental condition driving monsoon precipitation (Zhisheng et al., 2015). A predominance of rainfall during summer months, typically accounting for more than 70% of the total annual mean (Wang et al., 2011a) can be observed. Globally, there are six major monsoon regions: South and East Asia, Indonesia-Australia, Northern Africa, Southern Africa, North America, and South America (Chang et al., 2011; Gan et al., 2004; Rodríguez-Zorro et al., 2020; Zhou & Lau, 1998). Monsoon regions can present high nonlinearity and complexity in their hydrological processes (Turner and Annamalai, 2012). Consequently, these regions are vulnerable to climate variability and changes related to water availability, water security and food security (Turner et al., 2011).

Monsoon regions have faced difficulties related to population increase as well as agricultural challenges due to rainfall trends and variability (Gadgil and Gadgil, 2006; Shafqat et al., 2016; Turner and Annamalai, 2012; United Nations et al., 2014). Countries located in these regions are typically major agricultural exporters. Brazil and China, for instance, are among the top ten agricultural producing countries in the world (OECD, 2018; Verter, 2015). Considering this complexity, accurate prediction and representation of hydrological responses are necessary for the sake of water resource management and food security in these regions (Tan et al., 2019).

Hydrological models are powerful tools that can help support decision making in the water resource management process (Abbott and Refsgaard, 1996). Several hydrologic models have been used in different monsoon regions for such purposes. The HBV model (Lindström et al., 1997) was applied in Ethiopia (Worqlul et al., 2017), China (Chen et al., 2012) and Chile (Parra et al., 2018); TOPMODEL (Beven and Kirkby, 1979) in the USA (Houser et al., 1998), Japan (Ebata et al., 2018), and Benin (Le Lay et al., 2008); HEC-HMS (USACE-HEC, 2006) in the Himalayas (Azmat et al., 2020); SWIMM (Krysanova et al., 2000) in China (Gao et al., 2016); and the SWAT model (Arnold et al., 1998) in India (Anand et al., 2018; Wagner et al., 2011), Nepal (Thapa et al., 2017), Pakistan (Hussain et al., 2019), and Brazil (Bressiani et al., 2015a).

The contrast in rainfall volume during the wet and dry seasons makes application of hydrologic models in monsoon regions challenging. One of the main difficulties in applying these models in monsoon-driven environments is the fact that models maintain the value of certain key parameters unchanged over time. For instance, it is well known that infiltration parameters, such as hydraulic conductivity, are influenced by antecedent soil moisture (Hardie et al., 2012). It is therefore evident that some model parameter values are affected by seasonality and should be allowed to vary throughout the simulation period. Furthermore, as pointed out by Wagner et al. (2011) and Tan et al. (2019), limited data availability or outdated information often restrict model applications in monsoon regions. Balancing data requirements and accuracy in process representation is critical when choosing the model to be employed. SWAT has proven its capability to meet this balance (Wagner et al., 2011) in many places around the world, including monsoon regions (Gassman et al., 2007; Tan et al., 2019). SWAT is also one of the most widely used hydrological models around the world, with more than 4,000 published article, including 127 studies conducted in Southeast Asia (1990 - 2019) and 102 in Brazil (1990 - 2015) (Bressiani et al., 2015a; Douglas-Mankin et al., 2010; Tan et al., 2019; Tuppad et al., 2011).

However, SWAT has shown limitations in predicting floods and low flows, a recurring issue in monsoon-driven environments (Gebremariam et al., 2014; Pfannerstill et al., 2014; Zhang et al., 2015). SWAT incorporates dozens of well-known modules into its structure and because it is open-source, it is possible to develop and incorporate modifications to overcome some limitations. From a hydrological perspective, this is very helpful, since it allows SWAT to be adapted to specific regions with varying hydrologic characteristics. Regions such as northeastern Brazil (Gan et al., 2004; Silva and Kousky, 2012; Zhou and Lau, 1998), or other monsoon regions (Turner et al., 2011; Webster, 1987), as aforementioned, have distinct wet and dry seasons, and that seasonality can affect hydrologic parameters such as hydraulic conductivity (Hardie et al., 2012) or travel time (Rinaldo et al., 2011). The SWAT model was developed to be applied in agricultural watersheds in temperate regions, however, its robustness and flexibility have permitted its application in many areas across the globe, which has consequently exposed some limitations (Douglas-Mankin et al., 2010; Pang et al., 2020; Tan et al., 2019). To be effective, the SWAT model must be adapted for local peculiarities, challenges, and unique physical characteristics.

To remedy these problems, we propose key modifications in SWAT's runoff and baseflow modules to strengthen its application for monsoon regions leading to improved water management. SWAT uses the SCS-CN (the Soil Conservation Service – Curve Number) method to compute surface runoff. This is an empirical model developed by the Soil Conservation Service for estimating direct runoff from storm rainfall based on soil type, land use, the antecedent rainfall and depth of a storm (Williams et al., 2012). It is one of the most commonly used rainfall-runoff methods in the world and has proven quite reliable (King et al., 1999; Mullem et al., 2002; Williams et al., 2012). However, because SCS-CN was developed empirically and is often utilized in applications that go beyond its original concept, it has received criticism related to limitations (White et al., 2009). As Cheng et al. (2016) stated, SCS-CN does not take into account rainfall intensity and duration, because it is solely based on total rainfall depth. Another pitfall is related to the initial abstractions (Ia) term, which is part of rainfall depth after which runoff begins. The SCS-CN method assumes that Ia is a fraction of the potential maximum retention after runoff begins (S), i.e., $Ia = \lambda S$ ($0<\lambda<1$), and the values of λ was assumed to be 0.2. This signifies that λ remains the same regardless of the land use/cover or soil characteristics. Recent efforts have shown advantages in making the λ value more flexible (Bryant et al., 2006; Jacobs and Srinivasan, 2005; Woodward et al., 2003).

For baseflow and groundwater processes, SWAT uses an exponential decay function proposed by Sangrey et al. (1984) and Venetis (1969) in which the groundwater recharge is based on the fixed travel time or drainage time of the overlying geologic formations (Neitsch et al., 2011). However, in areas with intense wet and dry spells, travel time should be dynamic and vary throughout the seasons (Rinaldo et al., 2011). Groundwater-related variables are usually difficult to measure or to derive from other sources of data (Jie et al., 2011) and the variability in soil water content between soil layers can play a crucial role in modeling groundwater processes

(Seiler and Gat, 2007). Therefore, improving groundwater processes can lead to increased model performance and more accurate prediction of hydrological processes.

The present study proposes two modifications to the SWAT source code to improve the effectiveness of water management in monsoon regions. 1) an adaption allowing for a calibration procedure where initial abstractions, as well as other variables related to the SCS-CN method, can be adjusted by the user or by automated calibration software; 2) a new approach where the delay time for baseflows varies as a function of the Julian day, depending on the season, being longer in the dry season, and shorter in the wet season. Both modifications were tested separately, as well as together in a monsoon watershed in Brazil through a series of modeling experiments. The studied watershed is an important water resource for Brazil's capital city (Brasilia) and has recently experienced a water crisis.

7.2. Basic theory and new approaches

In the following sections, the SWAT conceptualizations related to surface runoff and groundwater estimation will be discussed. Also, new approaches conceived during this study will be described as an attempt to improve SWAT performance under the SCS-CN method as well as the simulated groundwater fluxes.

7.3. Swat model

SWAT is a semi-distributed hydrological model that allows for simulation at daily, monthly, and yearly time steps (Arnold et al., 1998). SWAT can be run as a standalone program or through interfaces coupled with GIS software such as ArcGIS or QGIS. In terms of hydrologic processes, SWAT simulates evapotranspiration, overland runoff, infiltration, lateral flow, and baseflow (Sophocleous et al., 1999; Srinivasan et al., 1998). Other model components include sedimentation, nutrient cycling, vegetation growth, management systems, bacteria, and pesticide fate and transport. The model dates back to the early '90s (Srinivasan et al., 1998) and has been constantly updated (SWAT2012 rev. 681 was released 8 June 2020). SWAT has been widely applied to assess hydrological dynamics (Buchanan et al., 2018; Jin et al., 2015;

Kim and Lee, 2009), environmental applications (Heuvelmans et al., 2005; R Jayakrishnan et al., 2005; Tian et al., 2017), agricultural management (Githui et al., 2016; Mwangi et al., 2016; Sunde et al., 2017), climate change (Ficklin et al., 2013; Jha and Gassman, 2014; Wang et al., 2012), and nutrient cycling (Morales-Marín et al., 2015; Pers et al., 2016; Zhang et al., 2017) with a great amount of published scientific papers (Douglas-Mankin et al., 2010; Gassman et al., 2014; Tuppad et al., 2011). SWAT provides two methods for estimating surface runoff: the Soil Conservation Service curve number procedure (CN) and the Green and Ampt infiltration equation (G&A) (Neitsch et al., 2011). Both methods have advantages and disadvantages, however, G&A requires sub-daily precipitation data as model input and has not shown superior results compared to SCS-CN (Bauwe et al., 2017; King et al., 1999). On the other hand, according to King et al. (1999), the SCS-CN method provides a simple and yet robust approach to simulate runoff. Almost all SWAT applications in the literature use the SCS-CN method.

7.3.1. SCS-CN Method

SCS-CN was, originally, the product of more than 20 years of studies in small watersheds seeking to understand connections between rainfall and overland runoff (King et al., 1999). Over the last 20 years, the SCS-CN method has been revised many times and adopted by many models, such as CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980), GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) (Leonard et al., 1987), SPUR (Simulating Production and Utilization of Range Land) (Hansen et al. 1992), SWRRB (Simulator for Water Resources in Rural Basins), WEPS (Water Erosion Prediction Project) (Williams et al., 1985), EPIC (Erosion Productivity Impact Calculator) (Williams et al., 1984), APEX (Agricultural Policy/Environmental Extender) (Williams and Izaurralde, 2006), and SWAT (Williams et al., 2012).

As mentioned previously, this method has limitations and there have been many efforts to improve upon it. For instance, Woodward et al. (2003) proposed changes to the classic formulation of λ based on field observations. The authors assumed that initial abstractions could change depending on land use and other physical characteristics. By considering several hundred study sites containing rainfall-runoff data, their findings indicate that λ=0.05 is a better representation than 0.2. Although good results were obtained by using λ with a constant value (0.05), Woodward et al. (2003) showed that a dynamic λ could lead to even better performance. Similarly, Bryant et al. (2006) suggested that λ should be less than 0.2 during small rainfall events (1mm/event), and greater than 0.2 during larger events.

Based mainly on Woodward et al. (2003) and other studies linked to his team (Hawkins, 2014, 1993; Mullem et al., 2002), researchers have tried to overcome these limitations of the CN method by developing new equations and new approaches in the SWAT model. Wang et al. (2008) applied three modified versions of the SCS-CN method based on Jain et al. (2006). The authors calculated λ as a function of S and P. Moreover, Wang et al. (2008) used varying SCS-CN values as a function of plant evapotranspiration (Neitsch et al., 2011), inserting a non-linear power function to calculate S. The authors also attempted simulations using λ as a fixed value of 0.05 and the default method as well. The results were comparable for all three approaches in predicting total streamflow, and these new approaches yielded better results estimating baseflow and water yield. Similarly, Pang et al. (2020) developed a method where λ varies as a function of slope, land use, and soil profile. Significant results were obtained by the authors, especially for the validation period, where the modified version outperformed the original SCS-CN method with Nash–Sutcliffe efficiency coefficient (*NSE*) (Nash and Sutcliffe, 1970) of 0.91 versus 0.73 in predicting streamflow.

White et al. (2009), using methods developed by Feyereisen et al. (2008), changed the original SWAT code to allow for fixed updates in *CN* values for agricultural lands depending on the day of the year instead of as a function of antecedent soil moisture content. In the growing season, *CN* values were reduced by 2.5 units, while during the dormant season it was increased by the same value. Additionally, based on Woodward et al. (2003) and Bryant et al. (2006), the authors changed initial abstractions from 0.2S to 0.05S. Their findings suggest that (i) changes in *Ia* increase the model’s accuracy, and (ii) seasonal *CN* variation yield only modest improvements.

Cheng et al. (2016) tested five approaches in SWAT to determine surface runoff, where three were based on default SWAT methods and two consisted of modified versions: (i) CN-ET, where *CN* values are modified as a function of antecedent climate instead of soil moisture storage; (ii) CN-Soil, the standard built-in option based on antecedent soil moisture condition; (iii) G&A, Green-Ampt approach; (iv) SWAT–WB, based on assumptions from White et al. (2009), where a ratio between storage and rainfall is used to determine flow; and (v) SWAT–VSA, grounded in the notion that different areas generate different amounts of surface runoff (Lyon et al., 2004; Schneiderman et al., 2007). In terms of streamflow simulations, SWAT–WB and SWAT–VSA did not show significant improvements compared to the traditional CN method, although results from the other two default methods (CN-ET and G&A) were inferior. SWAT–WB and SWAT–VSA obtained good results for soil moisture analysis.

Rajib & Merwade (2015) also proposed modification to the SWAT code, applying a time-dependent Soil Moisture Accounting (SMA) based on the SCS-CN method, wherein rainfall and runoff are considered within one particular simulation time-step as a rate in terms of rainfall intensity and runoff. The results presented good model performance, but the coefficient of determination (R^2) and the NSE values were only slightly better than the traditional SCS-CN method.

Singh & Goyal (2017) used a new approach proposed by Huang et al. (2006) and Mishra et al. (2014). Assuming the original CN method takes into account CN2 values defined for a slope of 5% (Sharpley and Villiams, 1990), an equation was developed to incorporate slope values ranging from 14% to 140%. The effect of the slope is then adjusted for each Hydrologic Response Unit (HRU). They observed significant improvements in model performance based on R^2 at two hilly watersheds: R^2 values were 0.40/0.49 in predicting streamflow and water yield whilst 0.58/0.61 from the traditional and modified versions respectively (calibration/validation in both models).

Clearly, there are some new approaches to the SCS-CN method, especially related to initial abstractions. Some have been tested in SWAT and have shown good results. However, these solutions are still specific to localities taking into account unique regional conditions. Therefore, we aimed to develop a novel approach by which λ can be changed throughout the model calibration process and can be employed at any catchment, regardless of climate, soil, slope and/or land use conditions. We modified the SWAT source code to allow for a calibration procedure in which initial abstractions, as well as other variables related to the SCS-CN method, can be adjusted by the user or by automated calibration software. From this point forward, our proposed approach will be referred to as **M_{CN}** (modified CN) and the default version as **M_0** (Original version).

7.3.2. SCS-CN theory and proposed modifications

The SCS-CN method relates event runoff depth to event precipitation depth through the following relationship:

$$\begin{aligned} &if \quad P > Ia \qquad && Q = \frac{(P - Ia)^2}{P - Ia + S} \\ &else && Q = 0 \end{aligned} \tag{1}$$

where Q is the storm runoff depth (mm), P is the event rainfall depth (mm), S is the potential maximum retention depth after runoff begins (mm) and Ia is the initial abstraction assumed to be fraction of S (mm), i.e., $Ia = \lambda S$. The parameter S is related to the dimensionless Curve Number (CN):

$$CN = \frac{25{,}400}{(254 + S)} \tag{2}$$

where the unit of S is mm in this equation. The λ value has been assumed to be 0.2 and this value has been widely used throughout the past decades. The CN values tabulated in the SCS handbook are only valid under the assumption of λ=0.2. However, as highlighted by Woodward et al., (2003) this proportion can change for different areas depending on land use, soil, slope, and other factors (Pang et al., 2020). In their research, Woodward et al. (2003) used data from 252 study cases and came up with 0.05 as a more suitable value for λ to represent the initial abstractions. Based on this, they developed the following relationships to relate the original S (in mm) and CN parameters ($S_{0.2}$ and $CN_{0.2}$) to new S and CN parameters corresponding to λ=0.05 ($S_{0.05}$ and $CN_{0.05}$).

$$S_{0.05} = 0.8187(S_{0.2})^{1.15} \tag{3}$$

$$CN_{0.05} = \frac{100}{1.1879\left[\frac{100}{CN_{0.2}}-1\right]^{1.15}+1} \tag{4}$$

Equation (3) can be generalized for any λ:

$$S_{\lambda} = \alpha S_{0.2}^{\beta} \tag{5}$$

from which we can derive the following relationship that transforms the *CN* values tabulated in the SCS-handbook, i.e., $CN_{0.2}$ to CN values corresponding to different λ, i.e., CN_{λ}.

$$CN_{\lambda} = \frac{100}{\frac{\alpha}{25.4}\left(\frac{25{,}400}{CN_{0.2}}-254\right)^{\beta}+1} \tag{6}$$

Note that equation (6) preserves the theoretical lower and upper limits of *CN*, i.e., $0 \leq CN_{\lambda} \leq 100$. We modified the SWAT code (version 664) and replaced traditional equations with this generic relationship. To do that, it was necessary to modify some of the model's modules, namely *modparm.f*, and *allocate_parms.f* in order to define new variables (λ, α, and β), and three subroutines, namely *curno.f*, *surq_daycn.f* and *dailycn.f*.

In this new model λ, α and β became calibration parameters. Inspired by the values of Woodward et al. (2003), we used the following distribution for these three new parameters (except for λ) during an automated calibration process using SWAT CUP (Abbaspour, 2015):

$\alpha \rightarrow$ U[0.20,1.50] (μ =0.85)

$\beta \rightarrow$ U[0.50,2.00] (μ =1.25)

$\lambda \rightarrow$ U[0.00,0.40] (μ =0.20)

7.3.3. Groundwater concepts

We proposed a new approach for the baseflow component of the SWAT model for better prediction of groundwater contribution to streamflow in areas where distinct wet and dry seasons prevail. Modifications to that component have also been proposed by other studies.

Zhang et al. (2015) tried to overcome limitations in SWAT’s groundwater module by calibrating seasons independently. The authors achieved good model performance, although their methodology consisted of using external java applications, instead of changing SWAT’s internal structure.

Luo et al. (2012) changed the original concept of groundwater in the SWAT model, using the deep aquifer as a second source of water, instead of a confined reservoir, since this water was considered as loss from the system. It is used as the same linear approach for both storages. Pfannerstill et al. (2014) developed a similar method using three reservoirs, transforming the shallow aquifer into fast and slow aquifers. Under their hypothesis, water is extracted from percolation in the shallow aquifer in two different delay times, and they maintain deep aquifer as confined storage. Shao et al. (2019) also developed a similar approach and tested it on a local system in China. However, they treated the deep reservoir as regional storage of water contributing to inter basins. Nguyen and Dietrich (2018) developed a modified SWAT from the same perspective. The authors changed the deep aquifer approach so that it represents intermediate and regional groundwater flows, not solely restricted to a subbasin. They used groundwater observation wells to create Thiessen polygons where the flow between cells follows Darcy's law. They achieved good results comparing simulated streamflows to the default model. Although useful, this approach lacks practicality, since it requires observational wells inside the area of study, which may be a limitation in many places.

On the other hand, based on Wittenberg's (1994) studies, some authors developed a nonlinear storage approach, maintaining the original model’s structure (2 reservoirs). It is worth highlighting studies by Gan and Luo (2013) and Jin et al. (2018), which changed the baseflow equation by adding two additional parameters to control baseflow. Similarly, Wang & Brubaker (2014) introduced a new parameter to modify SWAT's baseflow computation.

Another different approach couples SWAT with state of the art groundwater models, such as MODFLOW (Harbaugh, 2005). Bailey et al. (2017, 2016) developed a SWAT-MODFLOW framework to improve the groundwater component of SWAT. However, MODFLOW requires a substantially large number of input parameters (e.g., volumetric flux and hydraulic conductivity in all axis discriminated by cell grids) and is computationally demanding, which makes the model relatively complex and its application rather difficult (Bailey et al., 2017, 2016). Furthermore, the application of such models for data-scarce regions is problematic.

7.3.4. Modified Recharge Calculations (a new approach)

The total recharge for both shallow and deep aquifer in SWAT is calculated using the following relationship:

$$w_{rchrg,i} = \left(1 - \exp\left[-\frac{1}{\delta}\right]\right). w_{seep} + \exp\left[-\frac{1}{\delta}\right]. w_{rchrg,i-1} \qquad (7)$$

where, $w_{rchrg,i}$ is the amount of water entering the aquifers on day i (mm), $w_{rchrg,i-1}$ is the amount of water entering on day i-1 (mm) and w_{seep} is the total amount of water leaving the bottom of the soil profile on the day i (mm). SWAT partitions the total recharge between shallow and deep aquifers with a simple, constant coefficient. The parameter δ in equation (7) is defined in SWAT as "the delay time or drainage time (in days) of the overlying geologic formations" (Neitsch et al., 2011). Streamflow estimates from SWAT are very sensitive to this parameter, especially during baseflow periods. The SWAT theoretical manual provides guidelines for its estimation by referring to the study of Johnson (1977), but it is essentially a calibration parameter and is constant throughout the simulation period.

In regions with distinct wet and dry seasons, the water table height of the surficial aquifer can exhibit very dynamic behavior (Healy & Cook, 2002; Rasmussen & Andreasen, 1959). Therefore, we argue that the delay time (δ) should be dynamic to capture seasonality in such environments. Here, we propose a sinusoidal model for δ to capture this seasonality:

$$\delta(i) = \left(\frac{\delta_{max}-\delta_{min}}{2}\right).Sin\left(\frac{i-i_{max}}{365}\ .2\pi + \frac{\pi}{2}\right) + \left(\frac{\delta_{max}+\delta_{min}}{2}\right) \quad (8)$$

where i is the current day and i_{max} is the driest day of the year, δ_{max} is the maximum delay time and $\delta_{min}$is the minimum delay time. Note that this equation assumes maximum delay time occurs on the year's driest day. The driest day can be identified by looking at historic streamflow records, or through a simple test run with SWAT using real climate data.

We inserted Equation (8) into the SWAT source code for $\mathbf{M_0}$ and $\mathbf{M_{CN}}$ to better capture seasonality effect on groundwater recharge. We named modification of $\mathbf{M_0}$ with Equation (8) as $\mathbf{M_{GW}}$ and modification of CN as $\mathbf{M_{CN/GW}}$. This modification created 3 new variables: δ_{min}, δ_{max} i_{max}. Since δ is no longer required and i_{max} can be estimated from historical streamflow records, this new equation essentially introduces only one extra parameter that needs to be calibrated. To identify the best values for these new parameters, we also used the auto-calibration procedure in SWAT CUP.

7.4. Materials And Methods

7.4.1. Study area

The models $\mathbf{M_{CN}}$, $\mathbf{M_{GW}}$, and $\mathbf{M_{CN/GW}}$ proposed in this study (2.2.1 and 2.3.1) were tested along with the default model ($\mathbf{M_0}$) in the Rodeador watershed (111.56 km^2), located in the Federal District of Brazil (Figure 7-1). The watershed is located in the central part of the country between parallels 15 and 16 and with elevations ranging from 750 m to 1344 m above sea level. The land use in Rodeador is divided into agricultural, urban, and preserved areas. This watershed is the largest contributor to the Descoberto basin, which is responsible for supplying water to ~62% of the region's population – 1.85 million inhabitants (GDF, 2017). Brasilia has faced water scarcity problems over the last few years, especially in 2017, when the government declared a state of emergency (GDF, 2017). The state's population is estimated at around 3 million inhabitants, and projections for 2050 estimate an increase to almost 4 million (IBGE, 2020). The region is located in highlands containing multiple springs and therefore the Rodeador watershed can be considered of strategic importance for Brasilia’s water security. Water years 2015-2016 and 2016-2017 registered about 30% less of average annual precipitation (GDF, 2017), with 2015-2016 classified as a very strong El-Niño year (GGWeather, 2019). Monsoon climate in this region coupled with El-Niño (Gan et al., 2004) may present challenges to accurate modeling of this watershed’s water dynamics.

The Rodeador watershed has a streamflow gauge station located at its outlet (ANA code 60435200). The annual precipitation average (2005-2013) registered in Rodeador was 1477 mm (Agência Nacional de Águas - ANA code 01548006 and 01548007).

The weather in Brasilia is well defined by two distinct seasons, with a dry period lasting up to six months and having significant impacts on streamflow and groundwater levels (GDF and SEMA, 2012; L. D. A. Salles et al., 2018). The rainy season typically extends from November to April, and the dry season from May to October (Figure 7-2). Occasionally, these periods can vary slightly, however most rain falls during the months of December, January, and February (Alves et al., 2017).

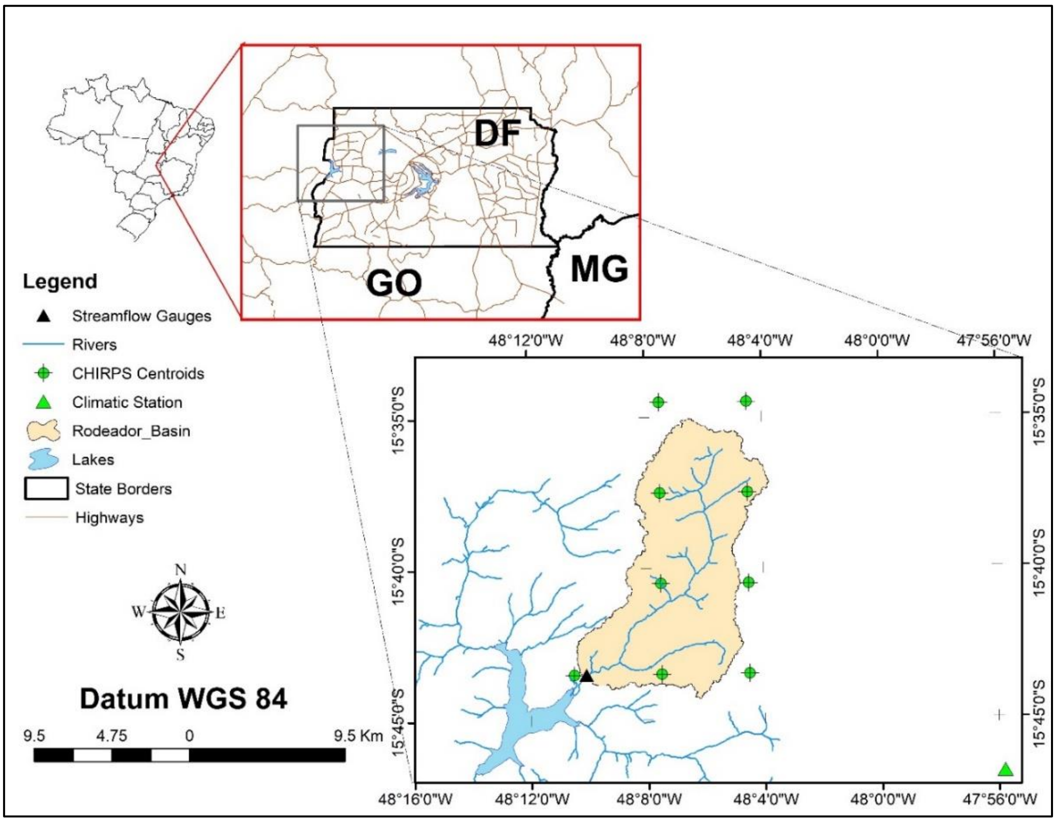


Figure 7-1. The study area.

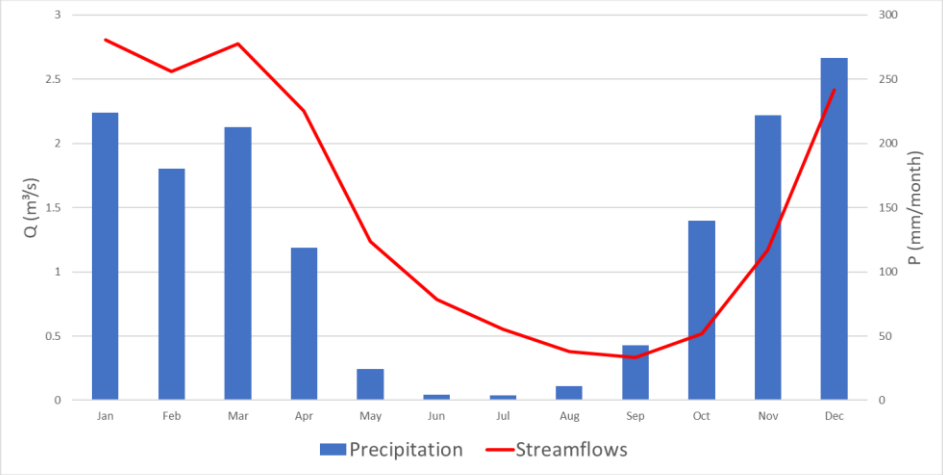


Figure 7-2: Average monthly variation in rainfall and streamflow from 2005-2013. Rainfall data is from CHIRPS

7.4.2. Datasets and input data

The Rodeador watershed was divided into 51 sub-basins according to the watershed's stream network (Figure 7-3a). The identified land use classes (IBRAM, 2013) describe 44% of the Rodeador watershed as agricultural (Figure 7-3b and Table 7-2), where the main activity is olericulture by small farmers (Figure 7-4). To maintain productivity throughout the year, farmers alternate the land between planting and fallow on a weekly basis (Lima et al., 2020). It is well known from past studies that water withdrawal from streams increase significantly during the dry seasons as a result of high irrigation demands (ADASA, 2012; Lima et al., 2020) leading to water shortage issues and water usage conflicts (Nunes and Roig, 2016; Oliveira et al., 2014). Forest in the watershed is dominated by three types of savannah: Mata, Cerrado, and Campo. Two key characteristics distinguish this vegetation: plant density and height. The denser and taller trees are locally known as Mata, whilst less dense and shorter plants are known as Campo (Pereira et al., 2011; Pinheiro and Monteiro, 2010; Ribeiro and Walter, 1998; Scholz et al., 2008). Cerrado is a savannah type vegetation with prevalence of shrubs and stunted trees and grass understory. The dominant soil classes in the Rodeador watershed are (Red/Yellow) Latosol and Cambisol (Reatto et al., 2004 - Figure 7-3d). A summary of data used in this project is described in Table 7-1.

Table 7-1. Summary of data used in the SWAT model set up and their sources

Data	**Source**
Sub-basins (Figure 7-3a)	Generated in ArcSwat 10.5
Land Use/Cover map 30m (Figure 7-3b)	IBRAM, 2013
Digital Elevation Model (DEM) 30m (Figure 7-3c)	Shuttle Radar Topography Mission
Soil Map 1:100.000 (Figure 7-3d)	GDF and SEMA (2012); Reatto et al. (2004)
Soil property data	Farias et al. (2008); Fiori et al., (2010); Lima et al. (2013); Lima et al. (2014); Reatto et al. (2000); Spera et al. (2005)

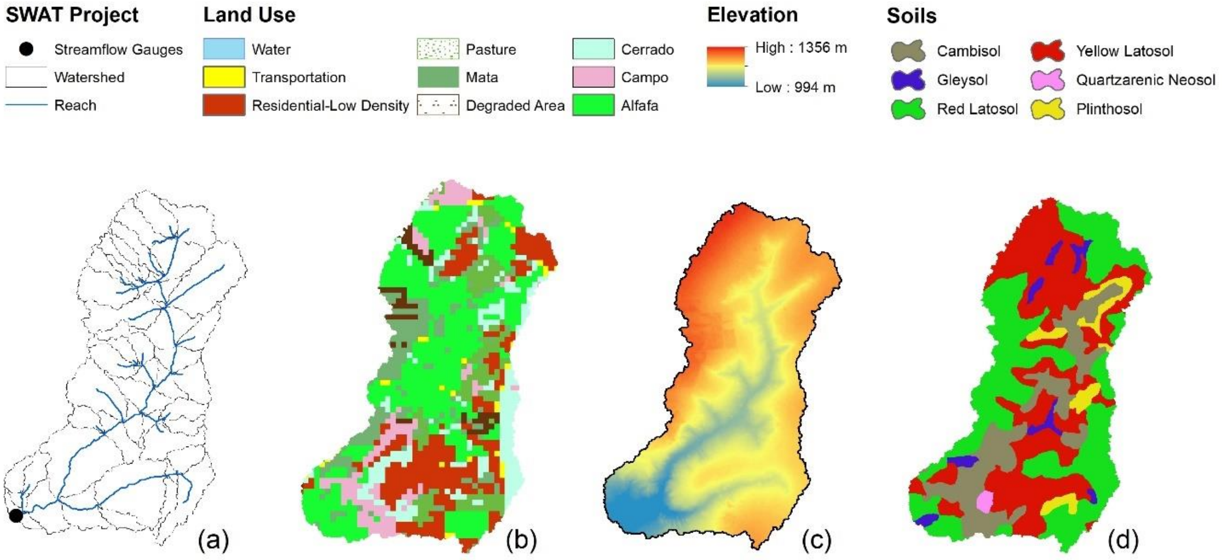
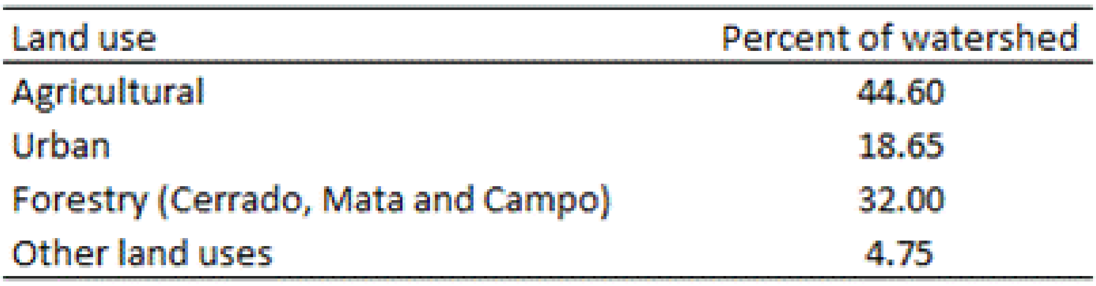


Figure 7-3: Spatial Data used in setting up the SWAT model at the Rodedador Watershed: a) Sub-basins b) Land Use/Cover c) DEM d) Soil Map

Table 7-2. Summary of land use/cover in the study watershed (IBRAM, 2013)



Land use	Percent of watershed
Agricultural	44.60
Urban	18.65
Forestry (Cerrado, Mata and Campo)	32.00
Other land uses	4.75

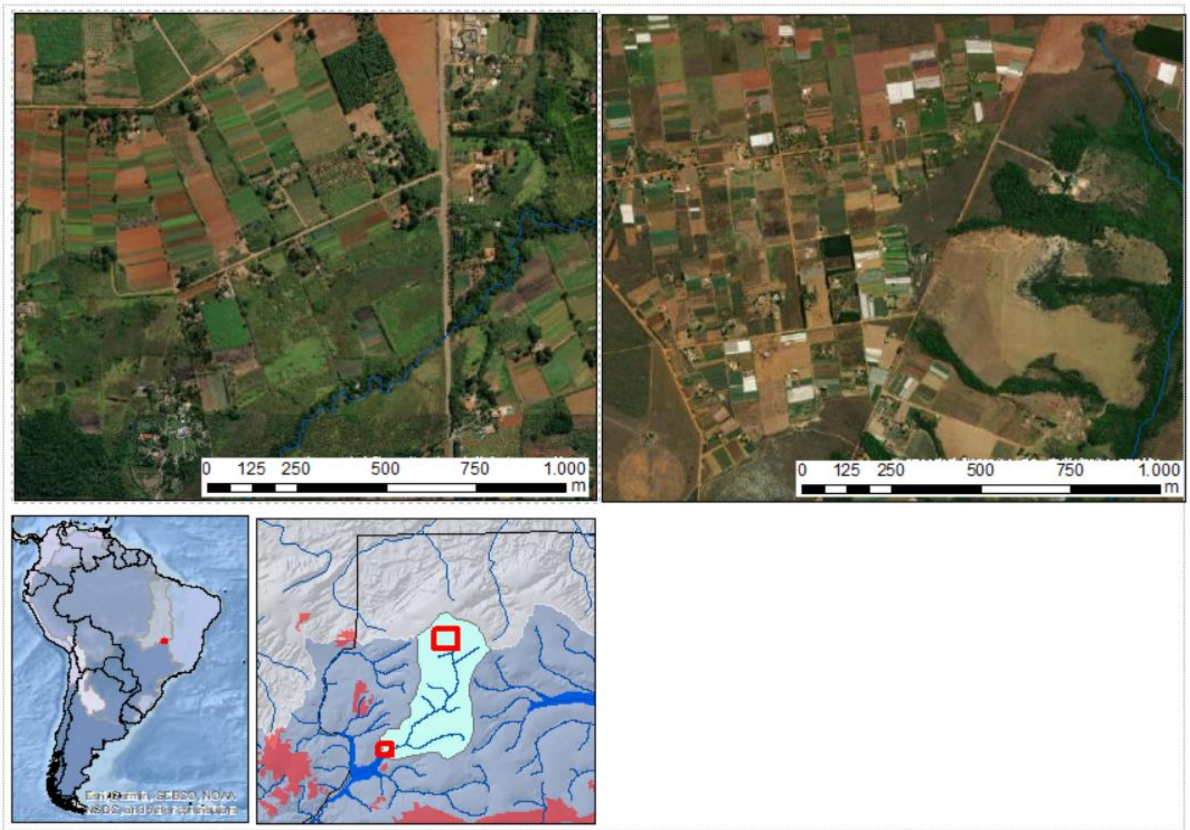


Figure 7-4: Typical land division in Rodeador Watershed. Source: Google Earth

The daily minimum and maximum air temperature, wind speed, relative humidity, and solar radiation data were collected from a national weather station (83377- INMET – Instituto Nacional de Meteorologia – National Institute of Meteorology) located 27 km from the Rodeador watershed outlet (Figure 7-1). Daily precipitation data was obtained from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS - Funk et al., 2015), and the daily streamflow data, from one gauge, was obtained from CAESB (Companhia de Saneamento Ambiental do Distrito Federal – Federal District Environmental Sanitation Company) for the period 1981–2015.

7.4.3. model calibration and validation

The SWAT model was calibrated using daily streamflow measurements from 01/01/1981 to 12/31/1999 and validated from 01/01/2000 to 12/31/2015, with a 3 years warm-up period. Five statistical rating metrics were used to verify the goodness-of-fit characteristics of the models ($\mathbf{M_{0}}$, $\mathbf{M_{CN}}$, $\mathbf{M_{GW}}$, and $\mathbf{M_{CN/GW}}$), as suggested by Moriasi et al., (2015). The Nash-Sutcliffe efficiency (*NSE*) (Nash and Sutcliffe, 1970), Percent Bias (*PBIAS*), Coefficient of Determination (R^2), *p-factor,* and *r-factor* were used as statistical metrics to compare observed and simulated streamflow.

The models were calibrated using the SWAT Calibration and Uncertainty Program (SWAT-CUP). SWAT CUP is a standalone program specifically developed for calibration of the SWAT model. It contains functionalities for validation and sensitivity analysis and five different calibration algorithms, of which SUFI-2 (Sequential Uncertainty Fitting version 2) (Abbaspour et al., 2015b) was chosen to test our methodology. SUFI-2 tries to capture most of the 95% prediction uncertainty (95 PPU) of a model, mapping all parameter uncertainties in an iterative process, based on an output variable obtained through Latin Hypercube Sampling (Abbaspour et al., 2015b). The analyses conducted here were performed at a daily time step along with multiple iterations of 500 simulations each starting with same parameter ranges. Following each iteration, a subsequent run was performed using the best range recommended by SUFI-2 until no further significant improvement was observed. We ensured that the recommended new ranges did not exceed minimum and maximum limits of each parameter. Additionally, the *p-factor* and *r-factor* generated by SWAT-CUP (Abbaspour, 2015) were used to assess the predicted uncertainty of the models. The *p-factor* gives the percent of observed data falling inside the 95% prediction interval (95PPU) and varies from 0 to 1, where 1 indicates 100% bracketing. The *r-factor* is the “ratio of the average width of the 95PPU band and the standard deviation of the measured variable” (Abbaspour et al., 2015b). The performance evaluation criteria used in this paper are described in Table 7-3.

Table 7-3: Performance Evaluation Criteria (adapt. from Moriasi et al., (2015) and Abbaspour (2015)).

Measure	Very Good	Good	Satisfactory*	Not Satisfactory*
R^2	R^2 > 0.85	0.75 < R^2 ≤ 0.85	0.60 < R^2 ≤ 0.75	R^2 ≤ 0.60
NSE	NSE > 0.80	0.70 < NSE ≤ 0.80	0.50 < NSE ≤ 0.70	NSE ≤ 0.50
PBIAS (%)	R^2 < ± 5	± 5 < PBIAS ≤ ± 10	± 10 < PBIAS ≤ ± 15	PBIAS ≥ 15
p-factor	-	-	*p-factor* ≥ 0.7	*p-factor* < 0.7
r-factor	-	-	*r-factor* ≤ 1.5	*r-factor* > 1.5

* Abbaspour (2015) suggests a “desirable value” instead of stages of performance for *p-factor* and *r-factor*.

The initial parameter range, the original values, and the “best” range (for the tested models) are shown in Appendix. The parameter selection and initial values were based on a general review of the literature along with specific studies previously conducted in the region (Castro, 2013; Lima et al., 2013; Reatto et al., 2000; Spera et al., 2005; Strauch and Volk, 2013).

7.5. Results and discussion

The results are presented and discussed in the following sections. The analysis is divided into four sub-sections: performance of the models, comparison with past studies, an assessment of the streamflow variability, and water budget inspection.

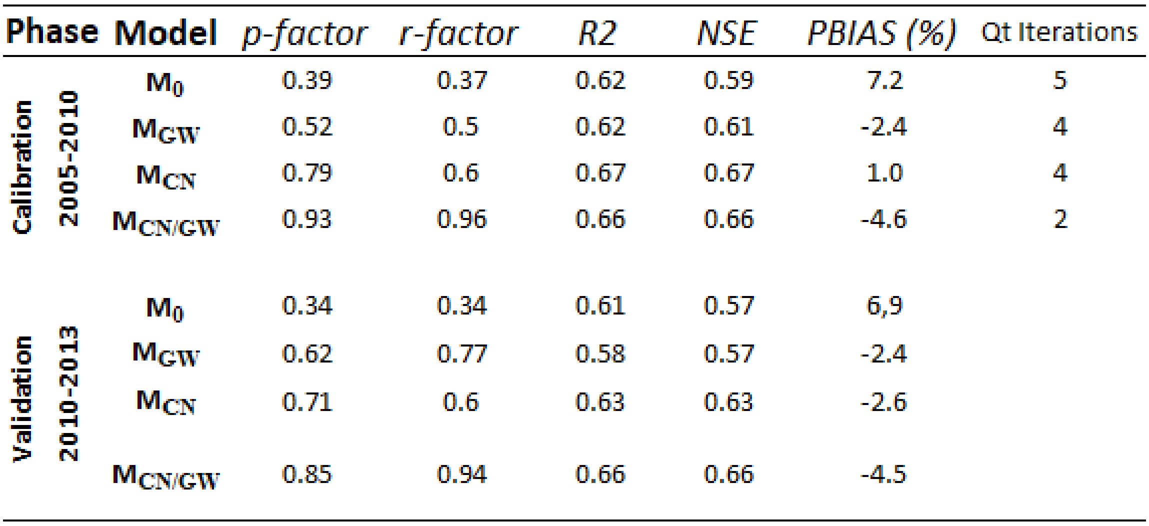
7.5.1. Streamflow calibration and validation

The performance of each model for simulating daily streamflow is summarized in Table 7-4. Figure 7-5 shows the daily time series of simulated and observed streamflow. Visually, all four models showed satisfactory performance. Models **M$_{CN}$** and **M$_{CN/GW}$** performed particularly well and showed improvements in simulating streamflow compared to the other models, as denoted by the increase in NSE, R^2, and

PBIAS (Table 7-4). It can be seen in Figure 7-5 that all models failed to capture some streamflow peaks, especially those in 1987, 1990, 1997, and 2007. This is a known problem in applying the CN approach for daily levels, as opposed to event level (e.g., a rain event spanning over two days is split into two separate events with the daily approach).

Based on the performance metrics shown in Table 7-4, for the calibration period, all evaluated SWAT models were classified as satisfactory ($0.60 < R^2 \leq 0.75$, $0.50 < NSE \leq 0.70$) according to Moriasi et al. (2015). $\mathbf{M_{CN}}$ achieved the best performance during the calibration period (the NSE and R^2 were 0.67), followed by $\mathbf{M_{CN/GW}}$ (0.66 for both indexes), $\mathbf{M_0}$ (0.62 and 0.59, for NSE and R^2, respectively), and $\mathbf{M_{GW}}$ (0.61 and 0.62, for NSE and R^2, respectively). There were significant differences in PBIAS, p-factor, and r-factor. The PBIAS index analysis classified the $\mathbf{M_0}$ as good ($\pm 10 \leq PBIAS < \pm 5$), whilst the modified versions were classified as very good ($PBIAS \leq 5$). The only version which achieved satisfactory performance in regards to the *p-factor* and the *r-factor* (p-factor ≥ 0.7 and r-factor around 1.0 and below 1.5), according to Abbaspour (2015), was the $\mathbf{M_{CN/GW}}$ version (0.93 and 0.96, respectively). For the validation period, all models were classified as satisfactory using the NSE index. Except for $\mathbf{M_{GW}}$ (R^2 is 0.58), all models were classified as satisfactory in terms of R^2. $\mathbf{M_{CN/GW}}$ performed slightly better than the other models. Analyzing PBIAS, $\mathbf{M_0}$ is classified as good while the other models fell into the very good category. The results from the *p-factor* and the *r-factor* were similar to the calibration period, wherein $\mathbf{M_{CN/GW}}$ was the only model that satisfied the accuracy requirements for satisfactory performance regarding *p-factor* and *r-factor* (0.85 and 0.94, respectively). According to Abbaspour *et al.* (2015), the stochastic concept behind SWAT-CUP proposes a range of parameters instead of unique values, which means that the uncertainty associated with each model parameter is taken into account. Consequently, satisfactory values for *p-factor* and *r-factor* indicate reduced uncertainty in the results based on the parameters' range for the simulations. Reduced uncertainty in model predictions is a fundamental step in modeling studies applied to water resource management (Beven and Alcock, 2012).

Table 7-4: Summary of model performances. *R^2*, *NSE*, and *PBIAS* correspond to the parameter set with the best model performance based on *NSE*.



Phase		Model	p-factor	r-factor	R2	NSE	PBIAS (%)	Qt Iterations
Calibration	2005-2010	M_0	0.39	0.37	0.62	0.59	7.2	5
		M_{GW}	0.52	0.5	0.62	0.61	-2.4	4
		M_{CN}	0.79	0.6	0.67	0.67	1.0	4
		$M_{CN/GW}$	0.93	0.96	0.66	0.66	-4.6	2
Validation	2010-2013	M_0	0.34	0.34	0.61	0.57	6,9	
		M_{GW}	0.62	0.77	0.58	0.57	-2.4	
		M_{CN}	0.71	0.6	0.63	0.63	-2.6	
		$M_{CN/GW}$	0.85	0.94	0.66	0.66	-4.5	

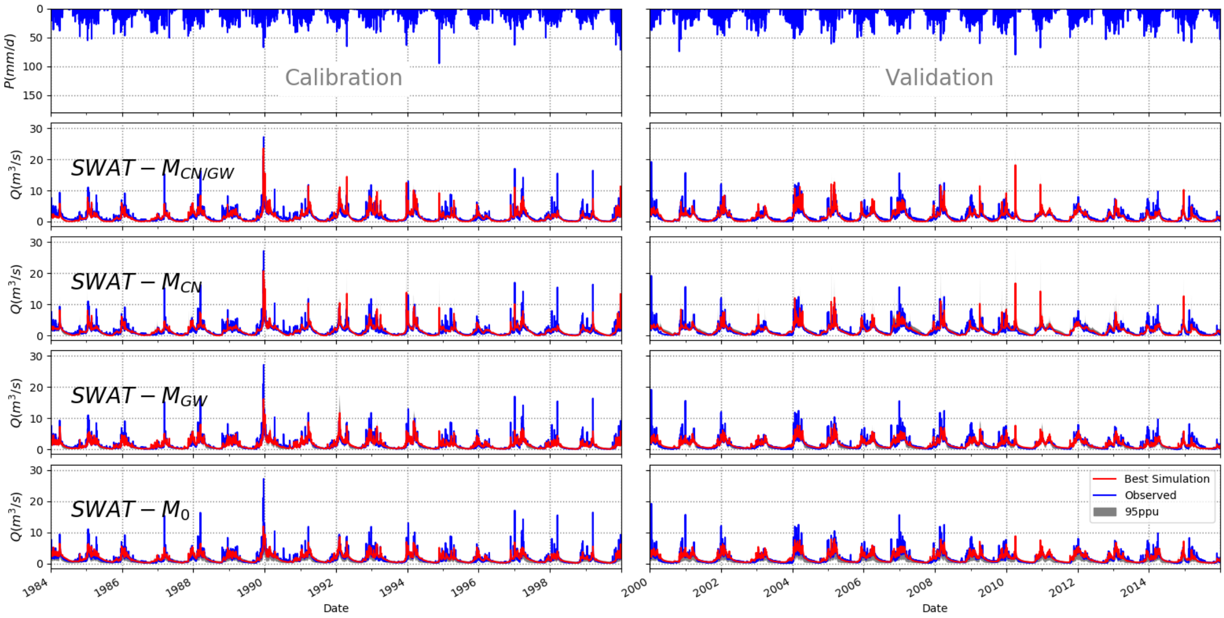


Figure 7-5: 95 ppu, best simulation, observed streamflows and precipitation referencing to the three models and the combined model

7.5.2. Comparison to past studies that modified CN module of SWAT

White *et al.* (2009), who developed CN updates based on seasons (growing and dormant) incorporated those in SWAT. They tested the methodology in watershed in Georgia (USA). Their results showed an increase in NSE by 0.02 (0.42 for the default, and 0.44 for the modified version) and had the PBIAS values reduced by 0.14% (0.38% and 0.52%, default and modified respectively).

Cheng *et al.* (2016), compared two modified versions of SWAT and the default SWAT version on the Jiaodong Peninsula (China), one based on White *et al.* (2009) and another related to CN based on the watershed's area. NSE increased 0.02 and 0.10 for the calibration and validation periods. Using the VE (volumetric efficiency) measure, performance was the same for all models.

The time-dependent Soil Moisture Accounting proposed by Rajib & Merwade (2015), applied to 2 watersheds in Indiana (USA), also achieved only slight improvements. The performance for NSE using the modified version was 0.02 and 0.06 higher than the default version for two different sites for calibration, but reduced, to 0.03, during validation for one site, and increased 0.01 for the other site.

Wang *et al.* (2008) proposed a method that considers the physical meanings of S and Ia/S and applied it in North Dakota (USA). The modified model achieved better results (0.10 units for NSE on average) compared to the default version for the calibration period, however results deteriorated during the validation period (0.05 units for NSE on average).

These findings demonstrate that, despite new developments and structural improvements, performance of these modified model versions is modest at best. The modified versions presented here in this current study are more efficient and resulted in concrete enhancement of model performance in simulating streamflow. Therefore, our proposed methodology can be considered adequate and valuable, especially for monsoon regions.

7.5.3. Performance of Flow Duration Curves (FDC)

We compared the FDCs of observed and simulated streamflows at the watershed outlet during, both, calibration and validation periods (Figure 7-6 a and b respectively). This assessment, according to Pagliero et al. (2014), aims to verify performance of the model for evaluation of flow regimes and can be especially valuable in differentiating the model's response under extremely low/high discharge conditions. Overall, $\mathbf{M_0}$ and $\mathbf{M_{GW}}$ underestimated the lower peaks ($Q_{obs} \leq 1.0$ m³/s)

45% and 30% of the time, respectively, throughout the entire simulation period (1984-2015). For calibration, **MCN/GW** and **MCN** demonstrated satisfactory performance. In contrast, for the validation period (Figure 7-6b), these models tended to overestimate low flows ($Q_{sim} \geq 35\%$). Both **MCN/GW** and **MCN** showed good ability in reproducing high flows ($Q_{obs} \geq 4.2$ m^3/s) and capturing peaks ($Q_{obs} = 27.16$ m^3/s in the calibration and $Q_{obs} = 19.18$ m^3/s in the validation).

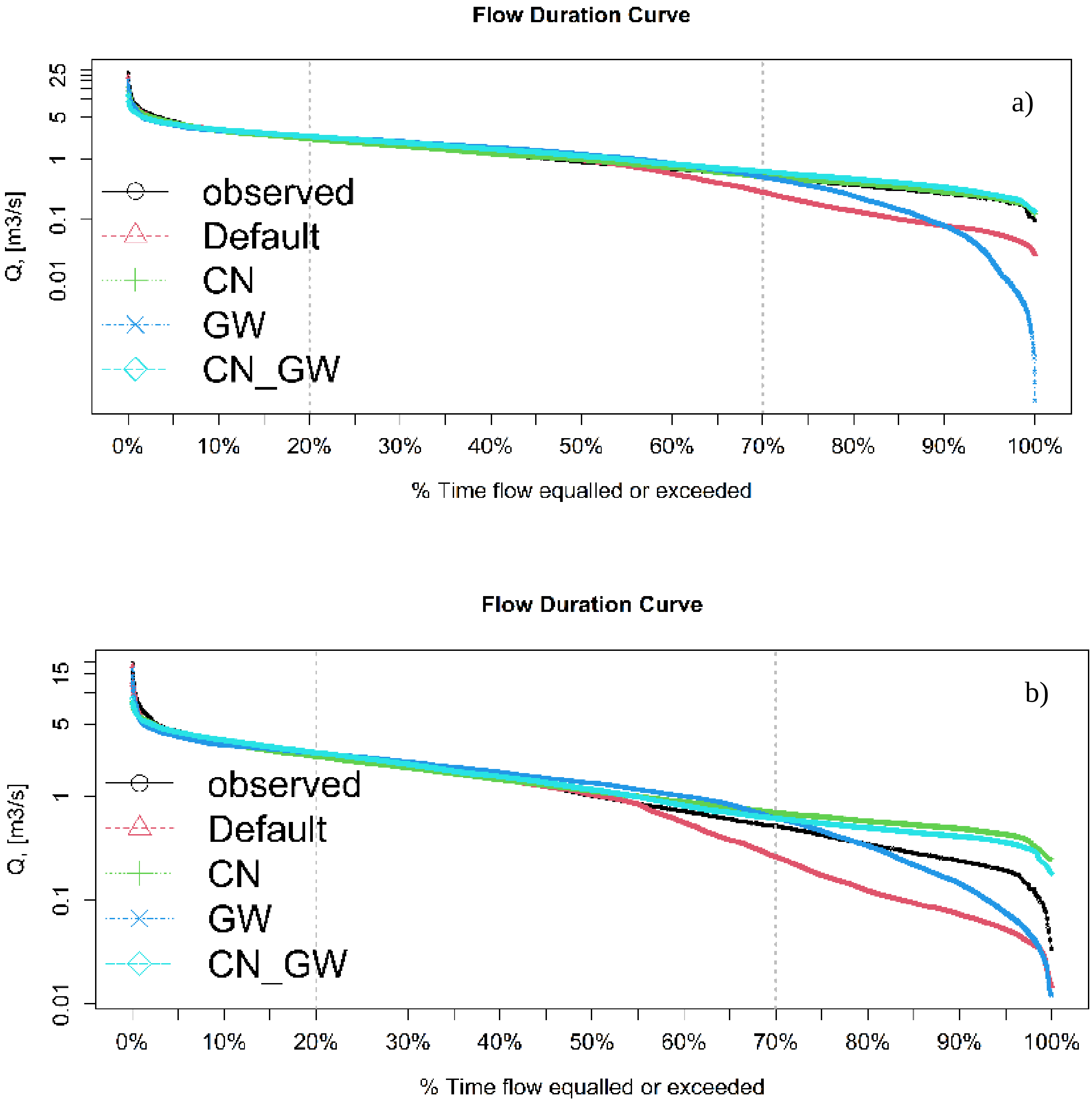


Figure 7-6: Flow Duration Curve in log function for a) Calibration b) Validation period.

Figure 7-7 shows four scatter plots containing observed and simulated streamflows for the four models. No significant difference was observed when $\mathbf{M_{GW}}$ was compared to $\mathbf{M_0}$. In contrast, the modified CN models ($\mathbf{M_{CN}}$ and $\mathbf{M_{CN/GW}}$) reduced the tendency of $\mathbf{M_0}$ overestimating streamflow. The $\mathbf{M_{CN/GW}}$ performed best, with most of the observed and simulated data points remaining near the line (1:1). These results underscore the superiority of $\mathbf{M_{CN/GW}}$ for water management. From a stakeholder's point of view, underestimating streamflows is preferable to overestimating as it leads to more conservative forecasting.

7.5.4. Water balance computation

Average annual water budgets were generated for each model based on the best simulation (

Table 7-5). For the calibration period, the highest surface runoff rate was observed for $\mathbf{M_{GW}}$ (298 mm), followed by $\mathbf{M_0}$ (166 mm). The $\mathbf{M_{CN}}$ and $M_{CN/GW}$ configurations yielded the same amounts (33 mm) of surface runoff. During validation, $\mathbf{M_{GW}}$ (281 mm) generated the highest surface runoff, followed by $\mathbf{M_0}$ (168 mm). The modified CN versions behaved the same as during the calibration period. This can be explained by underestimated streamflows of $\mathbf{M_0}$ and $\mathbf{M_{GW}}$ during the dry seasons, as previously illustrated in Figure 7-6 and Figure 7-7. The original CN equation tends to overestimate runoff events, leading to lower infiltration rates and consequently less groundwater contribution to streamflow. Following runoff computation SWAT simulates lateral flow, a slower process compared to surface runoff and responsible for supplementing streamflows during the dry season (Fan et al., 2007; Ponce and Lindquist, 1990). In both analyzed periods, the modified CN versions produced higher lateral flow values (258/322 mm in the calibration, and 390/422 mm in the validation, for $\mathbf{M_{CN}}$ and $\mathbf{M_{CN/GW}}$ respectively). Also, as Kannan et al. (2008) suggested, lateral flow increases may be related to runoff reduction, and this becomes particularly important in regions dependent on subsurface flows during dry seasons. SWAT then determines the total potential evapotranspiration (PET) and calculates the actual evapotranspiration (ET) based on canopy storage, soil water content, and plant characteristics (e.g., canopy height, stomatal conductance, LAI). The amount of rainfall lost to the atmosphere as ET can interfere with water cycle and plant development since ET generally represents the main component of the water budget. **MCN** presented the highest values of ET (808 mm and 897 mm) during calibration and validation, respectively. The latter may explain the reduced lateral flow when compared to **MCN/GW**. The reduced surface runoff can also explain the higher evapotranspiration values in **MCN** as there is more available water in the soil layers. The last water balance component computed in SWAT's workflow is groundwater contribution to streamflow. Extracted water from ET also reduces water availability for groundwater percolation. The contribution from the shallow aquifer in **M0** is higher than the modified versions (**MCN** **MGW**, **MCN/GW**), especially for the validation period. Water lost to the deep aquifer is negligible in all models. Our findings suggest that water budget, for the Rodeador watershed, is principally dominated by surface runoff and lateral flow, and those groundwater contributions have rather low relevance throughout the year.

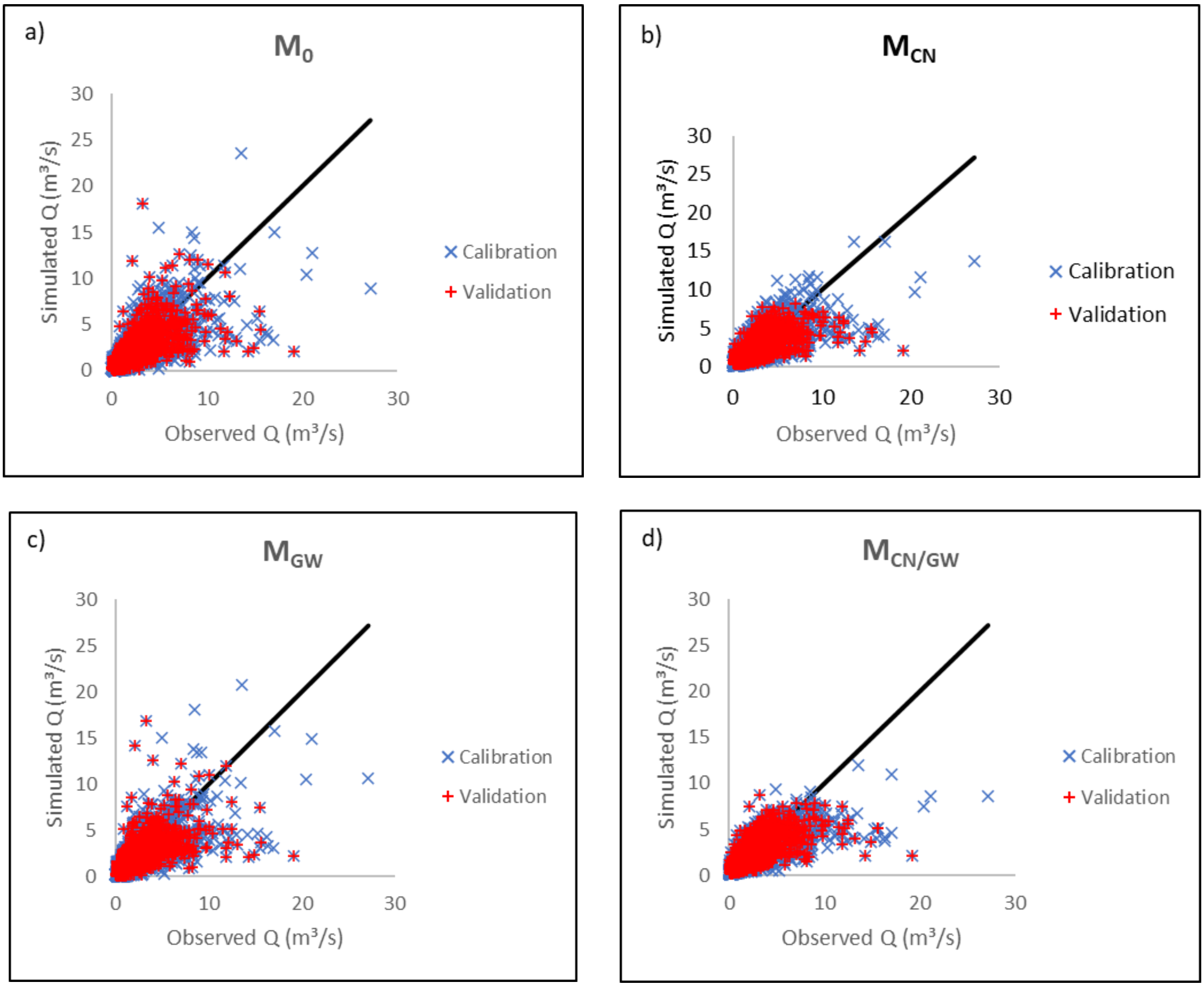


Figure 7-7: Observed versus simulated streamflow for the four models during both analyzed periods (calibration and validation)

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Table 7-5: Average annual basin values

	Calibration (mm)				Validation (mm)			
Variables	**M_0**	**M_{CN}**	**$M_{CN/GW}$**	**M_{GW}**	**M_0**	**M_{CN}**	**$M_{CN/GW}$**	**M_{GW}**
Precipitation	1445	1445	1445	1445	1457	1457	1457	1457
Surface Runoff	166	33	33	298	168	33	33	281
Lateral Flow contribution to streamflows	148	258	322	75	165	390	422	101
Groundwater (Shallow) contribution to streamflows	100	89	70	98	99	25	3	114
Groundwater (Deep) contribution to streamflows	20	23	14	0	20	9	7	5
Deep aquifer recharge	20	23	14	0	20	8	7	5
Total aquifer recharge (shallow + Deep)	427	351	194	186	389	141	107	247
Percolation from Soil to Groundwater	370	349	326	371	330	136	183	342
Total Water Yield to streamflows from HRUs	377	401	428	415	398	452	461	442
Evapotranspiration	763	808	762	701	806	897	809	740
Potental Evapostransporation	1583	1583	1583	1583	1933	1933	1933	1933

The proposed modifications to the SWAT model shed light on comprehension of hydrologic watershed processes afoot in this basin. Our findings consistently demonstrated the usefulness of our methodology and the advantages of the proposed model modifications compared to the default SWAT model structure.

7.6. **Conclusion**

This study proposed three modifications to the SWAT model source code. Modifications were made to the SCS-CN method used for estimating rainfall-runoff. The new methodology allows for the calibration of two parameters as functions of land use and soil. Additionally, the initial abstraction coefficient λ, which is currently fixed at 0.2 in the default method, becomes flexible under our approach. The third modification was made for the groundwater module. The delay parameter, responsible for controlling time travel for aquifer contributions, was modified as well in order to create a sinusoidal model, where the delay becomes longer during the dry season, and shorter for the wet season.

Our results consistently demonstrated improved performance of **$M_{CN/GW}$** in forecasting streamflow for a monsoon watershed covered by savanna vegetation. The calibration capacity included in Curve Number and groundwater parameters allowed for a more realistic and accurate representation of the physical processes present in the Rodeador watershed. Although **M_{CN}** and **M_{GW}**, individually, demonstrated benefits for the studied watershed, the combined model yielded better results. We acknowledge that testing of different watersheds may yield different results. Thus, we strongly encourage further testing of our model in other similar areas to improve the proposed methodology and enhance our understanding of surface and groundwater fluxes in monsoon regions. The well-defined seasonal characteristics of these regions (alternating wet and dry seasons) warrant the need to improve runoff analyses in the SWAT model because streamflows during the dry season are dependent on water infiltration from the wet season.

All modified versions showed improvements in streamflow prediction in the Rodeador Watershed when compared with the $\mathbf{M_0}$ version. The $\mathbf{M_{CN/GW}}$ version achieved the best results for most of the evaluation criteria, during both the calibration and validation periods. The baseflow contribution to streamflow may explain this since it is well-known that delay time and other physical soil physical may be affected by soil moisture and depth og the water table during the dry season. The results presented in the current study suggest that flexibility of updating CN values in our proposed modified SWAT models allows for additional changes in the SWAT source code. Consequently, it is possible to adapt the model to different land uses and scenarios that deviate from typical environmental conditions of the watershed present during model calibration. Furthermore, our methodology can be replicated in other regions where the default SWAT does not produce satisfactory results. The proposed improvements also led to reduced predictive uncertainty, and this is extremely helpful to decision-makers. Water management policies can be improved through the use of the proposed model, when applied in the Federal District of Brazil or other monsoon regions.

Model availability

The modified SWAT codes can be obtained by e-mailing the author: wellber@ymail.com.

7.7. **Appendix**

Table 7-6 Initial and final parameter's values.

Initial Values			Final Values											
			Default			GW			CN			CN-GW		
Method_Parameter	**Min**	**Max**	**Fitted**	**Min**	**Max**	**Fitted**	**Min**	**Max**	**Fitted**	**Min**	**Max**	**Fitted**	**Min**	**Max**
v__ALPHA_BNK.rte	0.00	0.70	0.41	0.31	0.62	0.29	0.24	0.42	0.50	0.42	0.71	0.31	0.01	0.47
v__ALPHA_BF.gw	0.00	0.70	0.79	0.53	0.81	0.59	0.40	0.65	0.75	0.61	0.87	0.43	0.20	0.59
r__BIOMIX.mgt	-0.90	0.70	0.66	0.53	0.78	-0.83	-0.99	-0.62	-0.68	-0.81	-0.51	-0.07	-0.99	-0.05
r__BLAI{122}.plant.dat	-0.90	0.90	0.23	0.12	0.36	-0.38	-0.62	0.23	0.25	0.01	0.67	0.33	-0.34	0.77
r__BLAI{123}.plant.dat	-0.90	0.90	-0.28	-0.81	-0.13	0.50	-0.39	0.50	0.48	0.24	0.74	-0.07	-0.26	1.01
r__BLAI{124}.plant.dat	-0.90	0.90	0.18	0.09	0.55	-0.55	-0.95	-0.50	0.42	0.04	0.45	0.22	-0.21	1.18
r__CANMX.hru	-0.90	0.90	-0.76	-0.86	-0.60	0.84	0.25	0.96	-0.70	-0.74	-0.38	0.52	-0.15	1.34
v__CH_K1.sub	0.00	150	221	169	236	89	75	132	6	0	28	44	1	84
v__CH_K2.rte	0.00	150	171	165	197	270	209	341	43	30	57	74	1	97
r__CH_N1.sub	-0.90	0.90	1.66	1.62	2.44	0.15	-0.35	0.56	0.59	0.10	0.84	-0.15	-0.15	1.35
r__CH_N2.rte	-0.90	0.90	0.66	0.21	0.82	1.78	0.74	1.80	-0.82	-0.90	-0.41	-0.16	-0.99	0.18
r__CN2.mgt______CAMP	-0.10	1.40	0.38	0.18	0.46	-0.37	-0.40	0.19	0.83	0.37	0.84	1.04	0.32	1.15
r__CN2.mgt______MATA	0.50	2.80	1.90	1.64	2.41	1.76	1.27	1.78	2.18	1.60	2.31	1.56	1.21	2.64
r__CN2.mgt______CERR	0.20	2.25	0.07	-0.05	0.55	1.13	0.78	1.69	0.34	-0.28	0.97	1.99	1.16	3.08
r__CN2.mgt______DEGR	-0.55	0.27	1.05	0.64	1.06	-0.52	-0.60	-0.37	-0.16	-0.25	0.13	0.34	-0.24	0.39
r__CN2.mgt______PAST	-0.28	0.99	-0.94	-0.95	-0.54	0.59	0.26	0.65	-0.37	-0.40	0.10	0.44	-0.63	0.45
r__CN2.mgt______ALFA	-0.50	2.25	-0.67	-0.93	-0.57	0.10	-0.37	0.32	1.49	0.80	1.77	2.47	0.70	3.10
v__DEP_IMP.hru	5000	8000	8202	7582	8403	7069	6072	7672	7165	6366	8154	5689	4152	6718
v__EPCO.hru	0.50	1.00	0.76	0.61	0.76	0.34	0.21	0.49	0.74	0.71	0.89	0.69	0.52	0.84
v__ESCO.hru	0.50	0.95	0.66	0.65	0.70	0.75	0.70	0.78	0.58	0.55	0.70	0.90	0.72	1.17
v__EVRCH.bsn	0.70	1.00	0.91	0.89	0.99	0.87	0.77	0.90	1.09	0.97	1.11	0.79	0.60	0.87
v__FFCB.bsn	0.00	1.00	0.52	0.48	0.67	0.60	0.39	0.63	0.60	0.45	0.83	0.88	0.37	1.12
v__GW_DELAY.gw	1.00	30.00	40.70	29.60	42.50	-	-	-	1.96	0.10	5.69	-	-	-
v__GW_REVAP.gw	0.02	0.20	0.23	0.17	0.26	0.05	0.01	0.09	0.26	0.21	0.29	0.12	0.09	0.24
v__GWQMN.gw	1000	3000	2700	2161	2907	2500	1943	2611	2307	2019	2921	1596	831	2277
r__OV_N.hru	-0.90	0.90	1.15	1.01	1.52	0.01	-0.38	0.10	-0.55	-0.95	-0.31	0.10	-0.36	0.72
r__RCHRG_DP.gw	-0.50	0.90	-0.07	-0.35	0.03	-0.96	-0.99	-0.49	0.32	0.15	0.41	0.42	-0.43	0.46
v__REVAPMN.gw	500	3000	3552	3198	4174	1257	456	1436	2697	2064	2944	1130	1061	2354
v__SURLAG.bsn	0.01	12.00	14.98	10.30	15.85	5.64	5.53	9.42	3.05	1.26	3.57	3.08	0.01	7.38
v__SHALLST.gw	1000	3000	1195	1052	1759	1930	1580	2023	2127	1728	2870	2589	1861	3583
r__SOL_ALB().sol	-0.90	0.90	-0.07	-0.16	0.29	1.10	0.70	1.25	-0.16	-0.22	1.07	0.17	-0.23	1.11
r__SOL_AWC().sol______PAST	-0.50	0.90	-0.08	-0.19	0.05	0.59	0.35	0.97	0.27	0.25	0.60	0.30	-0.03	0.90
r__SOL_AWC().sol______CAMP	-0.50	0.90	0.34	0.15	0.45	-0.34	-0.47	-0.12	-0.29	-0.58	-0.02	0.39	-0.21	0.53
r__SOL_AWC().sol______MATA	-0.50	0.90	-0.29	-0.38	-0.05	-0.03	-0.25	0.37	1.02	0.95	1.70	1.27	0.12	1.38
r__SOL_AWC().sol______CERR	-0.50	0.90	-0.15	-0.23	0.19	0.51	0.05	0.83	-0.87	-0.90	-0.49	0.08	-0.27	0.51
r__SOL_AWC().sol______ALFA	-0.50	0.90	0.32	0.22	0.48	0.59	-0.07	0.71	0.20	0.01	0.30	0.07	-0.08	0.77
r__SOL_K().sol__A	-0.50	0.90	0.99	0.48	1.07	0.25	0.10	0.46	0.70	0.58	0.93	1.29	0.10	1.30
v__SOL_Z(3).sol__A	3000	5000	4628	4281	4726	2204	2193	3155	5548	5103	6223	4211	3577	4731
r__SOL_ZMX.sol	-0.90	0.90	-0.17	-0.46	-0.10	-0.02	-0.05	0.05	0.11	0.10	0.42	1.03	-0.11	1.48
v__a.gw	0.20	1.50							1.46	0.82	1.48	0.32	0.01	1.00
v__b.gw	0.50	2.00							1.53	1.49	2.11	0.96	0.01	1.28
v__ʎ.hru	0.10	0.30							0.23	0.20	0.29	0.24	0.20	0.39

Table 7-7 Original parameter's values.

Parameters	Original Values	Parameters	Original Values
ALPHA_BF.gw	0.048	DEP_IMP.hru	6000
GW_DELAY.gw	31	CANMX.hru	0
GWQMN.gw	1000	CH_K2.rte	0
RCHRG_DP.gw	0.05	ALPHA_BNK.rte	0
SHALLST.gw	1000	CH_K1.sub	0
GW_REVAP.gw______PAST	0.02	EVRCH.bsn	1
GW_REVAP.gw______CAMP	0.02	FFCB.bsn	0
GW_REVAP.gw______MATA	0.02	SURLAG.bsn	4
GW_REVAP.gw______CERR	0.02	ANION_EXCL.sol	0.22
GW_REVAP.gw______ALFA	0.02	SOL_Z(3).sol__A	3500
CHTMX{122}.plant.dat	6	CH_N1.sub	0.014
CHTMX{123}.plant.dat	2	CH_N2.rte	0.014
CHTMX{124}.plant.dat	1	BIOMIX.mgt	0.2
GSI{122}.plant.dat	0.003	VPDFR{122}.plant.dat	3
GSI{123}.plant.dat	0.001	VPDFR{123}.plant.dat	4
GSI{124}.plant.dat	0.001	VPDFR{124}.plant.dat	3
EPCO.hru______PAST	1	BLAI{122}.plant.dat	3.5
EPCO.hru______CAMP	1	BLAI{123}.plant.dat	2.3
EPCO.hru______MATA	1	BLAI{124}.plant.dat	2.1
EPCO.hru______CERR	1	OV_N.hru_CAMP	0.15
EPCO.hru______ALFA	1	OV_N.hru_MATA	0.14
ESCO.hru______PAST	0.95	OV_N.hru_CERR	0.15
ESCO.hru______CAMP	0.95	OV_N.hru_DEGR	0.14
ESCO.hru______MATA	0.95	OV_N.hru_PAST	0.15
ESCO.hru______CERR	0.95	OV_N.hru_ALFA	0.06
ESCO.hru______ALFA	0.95	OV_N.hru_BERM	0.1

Table 7-8 Original Soil parameter's value based on layer number.

	Original Values - Soil Types						
Parameters	CX	FX	GX	LA	LV	LVA	RQ
SOL_AWC(1).sol______PAST	0.52	0.14	0.6	0.21	0.11	0.14	0.3
SOL_AWC(1).sol______CAMP	0.52	0.14	0.6	0.21	0.11	0.14	0.3
SOL_AWC(1).sol______MATA	0.52	0.14	0.6	0.21	0.11	0.14	0.3
SOL_AWC(1).sol______CERR	0.52	0.14	0.6	0.21	0.11	0.14	0.3
SOL_AWC(1).sol______ALFA	0.52	0.14	0.6	0.21	0.11	0.14	0.3
SOL_AWC(2).sol______PAST	0.16	0.14	0.13	0.21	0.11	0.14	0.08
SOL_AWC(2).sol______CAMP	0.16	0.14	0.13	0.21	0.11	0.14	0.08
SOL_AWC(2).sol______MATA	0.16	0.14	0.13	0.21	0.11	0.14	0.08
SOL_AWC(2).sol______CERR	0.16	0.14	0.13	0.21	0.11	0.14	0.08
SOL_AWC(2).sol______ALFA	0.16	0.14	0.13	0.21	0.11	0.14	0.08
SOL_AWC(3).sol______PAST	-	-	-	0.21	0.11	0.14	0.3
SOL_AWC(3).sol______CAMP	-	-	-	0.21	0.11	0.14	0.3
SOL_AWC(3).sol______MATA	-	-	-	0.21	0.11	0.14	0.3
SOL_AWC(3).sol______CERR	-	-	-	0.21	0.11	0.14	0.3
SOL_AWC(3).sol______ALFA	-	-	-	0.21	0.11	0.14	0.3
SOL_K(1).sol__A	31.8	240.62	20.25	56.97	54.53	59.41	260.04
SOL_K(2).sol__A	6.52	30.21	6.56	19.3	14.04	24.56	36.8
SOL_K(3).sol__A	-	-	-	6.375	5.28	7.47	12.08
SOL_ZMX.sol	1300	1300	1300	3300	3300	3300	3300
SOL_ALB(1).sol	0.1	0.08	0.08	0.05	0.03	0.08	0.2
SOL_ALB(2).sol	0.12	0.1	0.08	0.08	0.05	0.1	0.22
SOL_ALB(3).sol	-	-	-	0.08	0.05	0.1	0.22

Table 7-9 Original Curve Number's values based on hydrologic group.

	Original Values - Hydrologic Groups						
Soil Type	C	D	D	A	A	A	A
CN2.mgt______CAMP	75	81	81	41	41	41	41
CN2.mgt______MATA	35	40	40	25	25	25	25
CN2.mgt______CERR	40	45	45	30	30	30	30
CN2.mgt______DEGR	88	89	89	77	77	77	77
CN2.mgt______PAST	79	84	84	49	49	49	49
CN2.mgt______ALFA	72	79	79	31	31	31	31
CN2.mgt______BERM	72	79	79	31	31	31	31

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8. INTEGRATED WATER MANAGEMENT SYSTEM BASED ON SWAT/SWAT CUP

8.1. Introduction

In 1997, the World Meteorological Organization (WMO) published a series of documents analyzing the world's freshwater resources. Estimates suggested that by the year 2025 two-thirds of the world population would be suffering from water stress (WMO, 1997) with significant consequences for developing countries where urban occupation is higher than compared to developed countries and because these regions lack the necessary infrastructure to confront this demand (Kjellén and McGranahan, 1997). Padowski and Gorelick (2014) demonstrated that 31 cities with more than 750,000 inhabitants will face water vulnerability by 2040, which means there is an urgent need for better management of these resources.

Historical requirements related to the multiple-use of water resources, especially in preventing water scarcity, led to construction of dams, aqueducts, pipelines, and other structural engineering projects beginning in ancient times, and expanding greatly throughout the 20th-century (Biemans et al., 2011; Gleick, 2003). Allocation and storage of water required development of complex management systems, making use of mathematical models (Porto et al., 2003). In general, these models were created to improve understanding of environmental behavior (Hipel, 1993), however models usually present some uncertainties (Beven and Freer, 2001). To counterbalance intrinsic deviance and enhance the model performance, the optimization of simulation models was proposed (Loucks, 1993). Decision Support Systems (DSSs) were developed to improve the representation of a model and allow for its operation (Loucks and Van Beek, 2017).

DSSs can play a significant role in supporting generation of future scenarios (Ahmadi et al., 2020) and reduction of model uncertainty (Su et al., 2020). Reliable information about trends related to water resources based on changes in climate, land use, and water demand are critical for making decisions related to water resources management (Dong et al., 2013). Based on expected water scarcity scenarios (Padowski and Gorelick, 2014; Vörösmartry et al., 2000) and the need to better understand models and water demands, DSSs were created and have been improved upon over the years (Qian et al., 2011; Teodosiu et al., 2009).

Because water resource management is specific to each country/region, based on elements like culture, geography, history, and economy, DSSs are generally unique to the locations where they are applied (Jonch-Clausen, 2004). This fact led to the development of many DSSs around the world (Qian et al., 2011; Teodosiu et al., 2009). Likewise, different models have been developed to be used within DSSs, based on differing assumptions (Devia et al., 2015; Tomlinson et al., 2020). The development of a DSS based on local data, using well-known models that have proven reliable for the study area is of paramount importance (Mohammed et al., 2018; NASEM, 2018; Qi et al., 2018).

The Federal District of Brazil (Brasilia) has experienced water crises in recent years, and timely solutions were developed in order to provide information about water conditions to decision-makers (Barcellos et al., 2018; Mello et al., 2018). In the present study, a new DSS is being proposed, utilizing the renowned model SWAT (Soil and Water Assessment Tool) along with the optimization program SWAT Cup (SWAT Calibration and Uncertainty Programs) in order to improve water management in the city. The proposed system incorporates both tools in an integrative approach generating streamflows and reservoir volumes (chapters 5 and 7). A main focus of this project is the reduction of the gap between theory and application (i.e., academy and decision-makers) found in many models around the world.

8.2. The development of the Integrated System

The proposed DSS combines a hydrological model and an optimization tool. The model was used to assess streamflows and storage volume of the water supply reservoir, based on land use, topography, and climatological information, and the optimization tool allowed for estimation of optimal model parameters, and predictive model uncertainty. In the following sections, the region for which the system was developed will be described and the model, the optimization tool, and the integrated system will be explained.

8.3. **Study Area**

The Federal District (FD) is a planned territory chosen as the location of the Brazilian capital city, Brasília. It was created to shift governmental functions away from well-developed southern coast to underdeveloped regions in the interior of the country (Stephenson, 1970). It was inaugurated in 1960, and designed for a maximum population of around 600,000 inhabitants (Madaleno, 1996). Today, the FD has almost 3 million people (IBGE, 2020) and has undergone a dynamic process of urbanization (94% of the population lives in urban areas) (Lorz et al., 2012) and expansion of agricultural activity (Lorz et al., 2016). Freshwater comes from three reservoirs, responsible for 82% of the total water supply: Santa Maria, Descoberto, and Paranoá (Barcellos et al., 2018). The last was included as an emergency resource in 2018 (Barcellos et al., 2018). Another 5% of the total water supply comes from groundwater (de Moraes et al., 2008), and the remaining demand is supplied by direct withdrawal from streams (Vasyukova et al., 2012).

Initial planning suggested that population growth could affect life quality in the city (Madaleno, 1996), and future scenarios in 2010 predicted that the city would face problems related water availability (Aster et al., 2010). Also, in 2010, according to the water supply company, water demand had exceeded the system's capabilities (Kalbus et al., 2012; Vasyukova et al., 2012) and some rivers have seen significant decreases in baseflow discharge (Lorz et al., 2012). This imminent situation, coupled with consecutive years (2016, 2017, 2018) of observed rainfall equivalent to 75% of the historic average, led to crisis conditions for that period (Lima et al., 2018). The government managed to control multiple uses and ensure water security, prioritizing human water supply (Barcellos et al., 2018; GDF, 2017).

8.4. **Reservoir Simulation and Scenarios applied in FD**

During the crisis, a model based on water balance and annual rainfall was developed by the Federal District's Water, Energy and Basic Sanitation Regulatory Agency of the Federal District (ADASA) to generate future scenarios for the main reservoirs areas, using historic streamflows as input data to assess reservoirs volumes as depicted in Figure 8-1 (Mello et al., 2018). Monthly streamflows from past years were selected as main inputs, where dry, average, and wet hydrological historic data were used to generate rule curves for the reservoirs based on conservative, normal and optimistic scenarios, respectively. Average evapotranspiration and rainfall were also used to estimate precipitation and evaporation over the reservoir surface. Historic withdrawals by the water supplier and expected agriculture demands were considered as outflows for the model. Based on the conservative scenario, the government monitored observed volumes where a decrease in the water levels (falling below the level predicted by the rule curve) led to restrictions in water withdrawals (agriculture and water supply). The rule curve for the year 2017 is presented in Figure 8-2. This model was strictly based on historical data, where climate and land-use changes could strongly impact the results. The assumption was that similar behavior can be expected in streamflows in future years. However, one can expect some variation and it is unlikely that the exact same conditions will be repeated in the future (WMO, 2009c). This type of procedure is worked well as depicted in Figure 8-2 but this methodology may have problems in future years since it is not based on watershed properties as soil moisture or land use.

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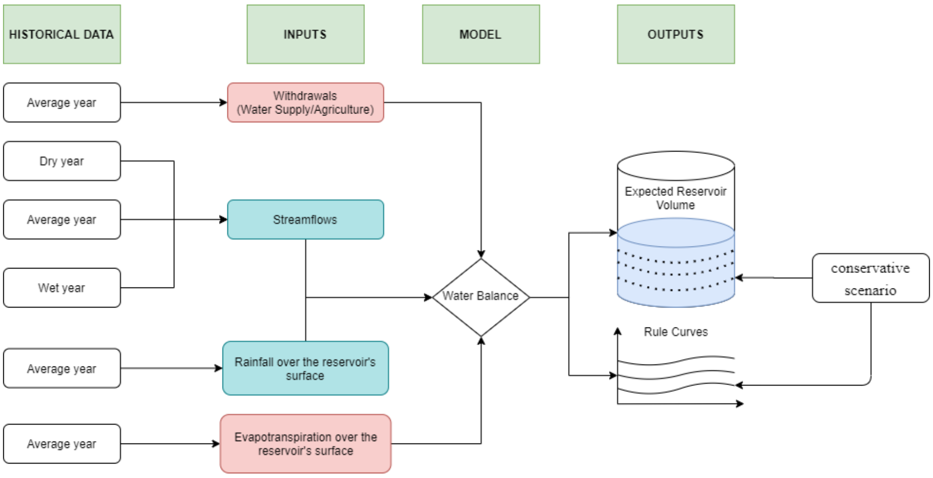

Figure 8-1. Diagram representing the current rule curve generator system

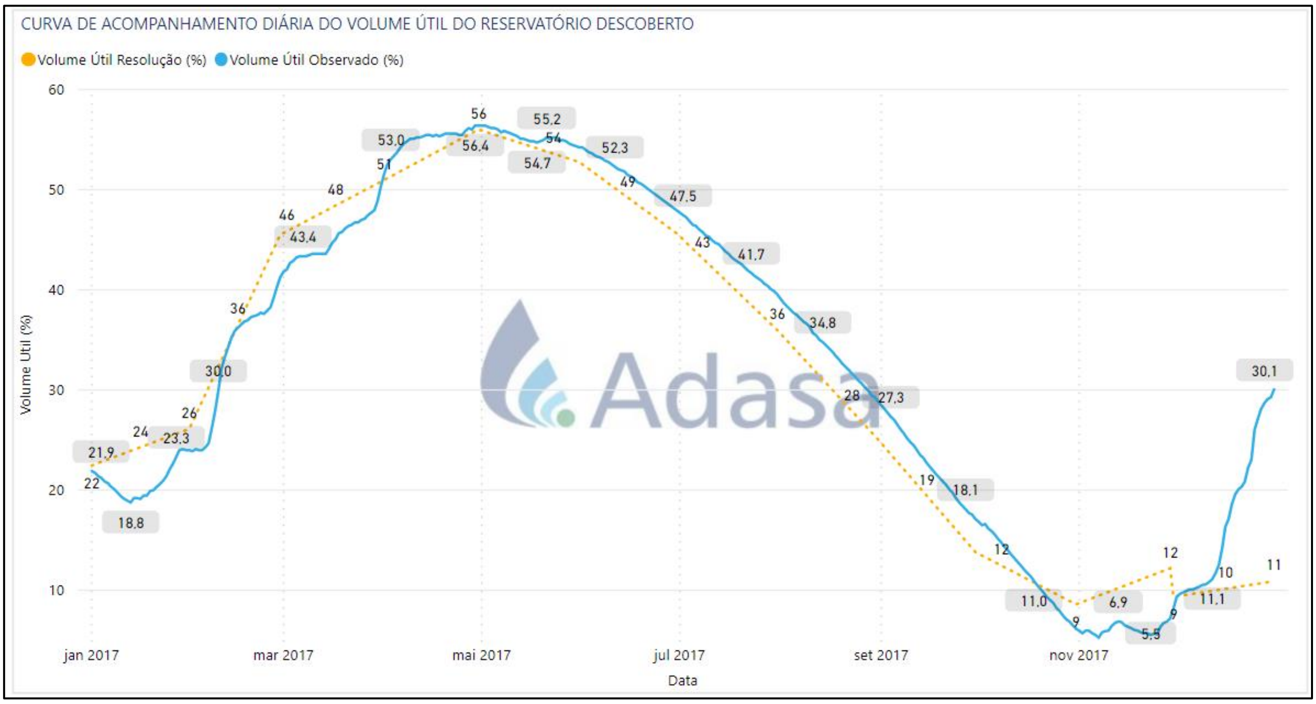

Figure 8-2. Rule Curve proposed by ADASA for the year 2017. The dotted yellow line means the proposed rule curve for the reservoir, and the solid blue line represents the observed reservoir's volume. This graph is available on the agency's website: https://app.powerbi.com/view?r=eyJrIjoiMGQxNGExZjItZWVlMi00NDEyLTk4YjItMWYwMDU3Y2Q0MzQ0IiwidCI6IjczZGJmMTMyLWE0YTQtNDkwMy1hYzI2LWJiMjhmY2Y3NDdhNCJ9

8.5. The Soil Water Assessment Tool (SWAT)

SWAT is a semi-distributed hydrological model that simulates streamflows and some water quality variables for daily, monthly, or yearly time intervals (Arnold et al., 1998). SWAT predicts evapotranspiration, overland runoff, infiltration, lateral flow, baseflow, and water table heights (Sophocleous et al., 1999; Srinivasan et al., 1998). It also simulates water quality variables, such as sediments and nutrients, bacteria, and pesticides, as well as vegetation growth, management practices, point sources, etc. The model has been in development since the 1990s (Srinivasan et al., 1998) and it has been constantly updated (SWAT 2012 rev. 681 was released 8 June 2020). SWAT has been widely applied to assess hydrological conditions in many regions throughout the world (Douglas-Mankin et al., 2010; Gassman et al., 2014; Tuppad et al., 2011), and has contributed to water management (R. Jayakrishnan et al., 2005).

The SWAT modeling process can be divided into three stages: construction of the database, configuration, and simulation. In the first stage, it is necessary to verify (or insert) parameters related to soils, plants, and other elements present in the watershed. In the configuration stage, the user needs to create a project inserting spatial information relative to watersheds (Digital Elevation Model, Soil Types, Land Use, and climatological data). The climatological data required depends on the method chosen to assess evapotranspiration. The default method is Penman-Montieth, which requires measurement of temperature, relative humidity, wind speed, and solar radiation. Subwatersheds and HRUs (Hydrologic Response Units) based on land use, soil types, and slopes are also created in this step. In the last stage, a simulation is performed to produce model outputs such as evapotranspiration, streamflows, and reservoir volume, etc.

8.6. SWAT Calibration Uncertainty Procedures (SWAT CUP)

Abbaspour *et al.* (2015) suggested the best way to evaluate the strength of a model is by performing an uncertainty analysis. SWAT CUP was developed based on this philosophy. It is software for calibration of the SWAT model, where the user can calibrate and validate the model as well as run sensitivity and uncertainty analyses

(Abbaspour, 2015). Of the SWAT Cup optimization programs, SUFI-2 (Sequential Uncertainty Fitting version 2) was chosen for this study. The SUFI-2 method combines elements from GLUE (Generalized Likelihood Uncertainty Estimation, Beven and Binley, 1992) and the gradient approach (Kool and Parker, 1988), and is modified to allow for a global search procedure (Duan, 2002) for the sets of parameter values (Abbaspour et al., 2004). The sets of parameter values are created using the Latin hypercube sampling process (McKay et al., 1979) and the optimization process is conducted by minimizing deviations between observed and simulated streamflows as described by Kool and Parker (1988). The same process can be used for water quality variables and reservoir volume (Abbaspour et al., 2007). It is recommended to run SWAT at least 500 simulations for each iteration (Abbaspour, 2015), and generally, it is necessary to have three to five iterations to obtain satisfactory results (Abbaspour et al., 2015b).

SWAT Cup generates performance measures such as R^2 and *NSE* (Nash-Sutcliff Efficiency). Additionally, it estimates two new statistics: *p-factor* and *r-factor*. The *p-factor* describes the percent of observed data falling inside the 95% prediction interval (95PPU), varying from 0 to 1, where 1 indicates 100% bracketing (Abbaspour et al., 2015b). The *r-factor* is the “ratio of the average width of the 95PPU band and the standard deviation of the measured variable” (Abbaspour et al., 2015b). Based on the premise that it is impossible to find the true set of parameter values among *n* sets of parameter values (Beven and Binley, 1992), the SUFI-2 algorithm finds a “best range” for each parameter (Abbaspour et al., 2004). The *p-factor* and *r-factor* are responsible for assessing uncertainty of the models, evaluating all results generated by the model correlated to all used sets of parameter values. This procedure is useful for decision-makers since it uses generated data to provide information for risk analysis(Beven and Binley, 1992).

8.7. **An Integrated Water Management System based on SWAT/SWAT Cup (InMaS)**

Integrated water resource management can be understood as a global process where the management of water and related resources are needed to achieve benefits for society (GWP, 2000). WMO (2009b) suggests the evaluation of at least three factors: 1 - the availability of water sources (surface and groundwater) and their quality; 2 - environmental stressors such as susceptibility to erosion, irrigation, punctual and/or diffused sources of pollution, loss of natural habitats; 3 – degree of integration among economy, society, and environment, considering stakeholder involvement.

The proposed system aims to be part of an integrated system. Both surface water and groundwater demand will be considered, in addition to information like land use and irrigation demands. Moreover, future scenarios can be generated in order to facilitate the decision-making in questions related to the economy, society, and the environment. A web-interface will be generated allowing smart functions and favoring communication with society (Su et al., 2020). Risk analysis based on environmental variation and water allocation supported by future scenarios will also be considered (Pahl-Wostl, 2006). Some of these dimensions were previously considered during the water crisis in FD, especially connecting with society through public hearings and providing public access to hydrological information hosted by an official web-page (Barcellos et al., 2018).

The system was designed to be operated through a web-based application where commands can be executed by decision-makers with or without advanced technical hydrologic knowledge. The results are displayed in user-friendly dashboards to facilitate the analysis. The proposed DSS system (in Figure 8-3) was divided into two main steps: *Calibrate/Validate* and *Forecast*.

The preparation of the model occurs in the first step and must be processed using the ArcSwat tool by the ArcGis program (it is also possible to use the Qgis/QSWAT) (Srinivasan, 2012). In this phase, the user must follow the cited stages detailed in the The Soil Water Assessment Tool (SWAT) topic (Section 8.5) to construct the model, providing information such as land/cover use, soil types, Digital Elevation Model (DEM), climate information (the required data are solar radiation, wind speed, relative humidity, solar radiation, and rainfall), and water demand related to the specific watershed. Figure 8-4 illustrates this process.

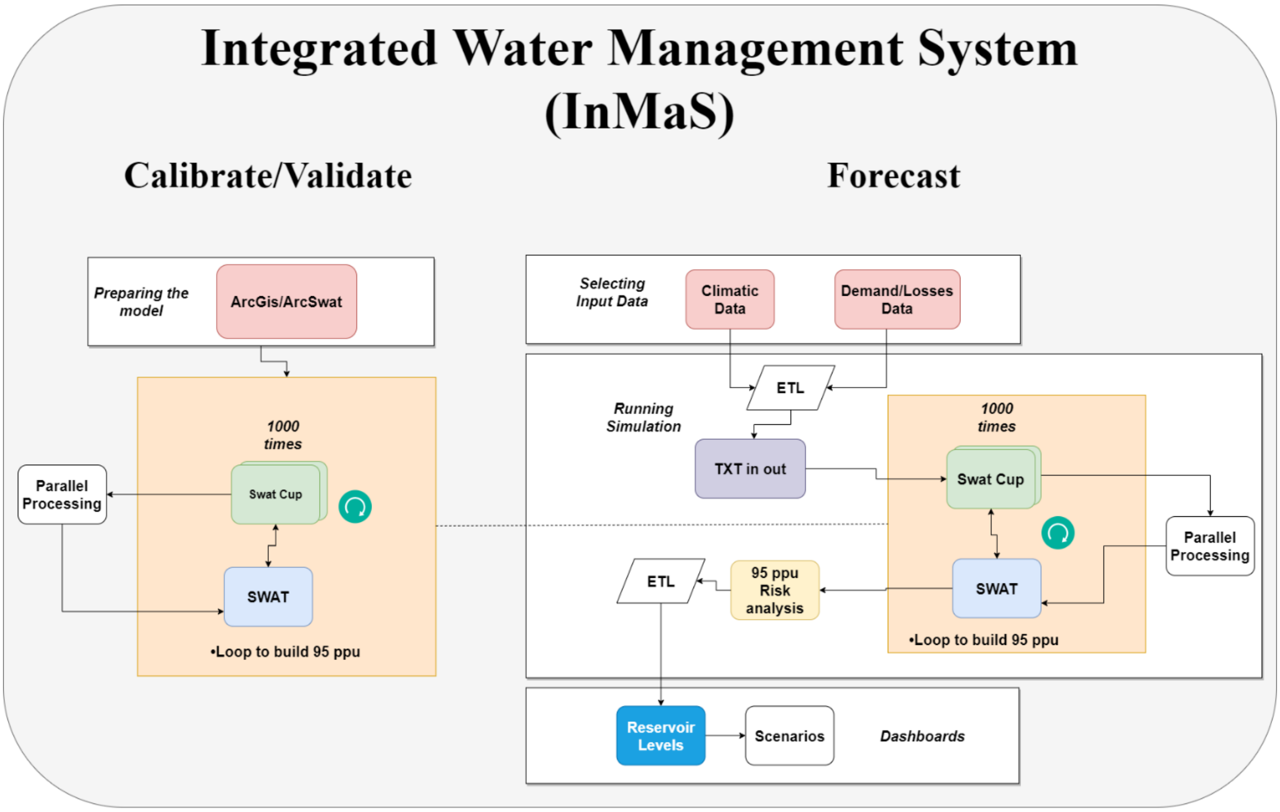

Figure 8-3: Proposed System

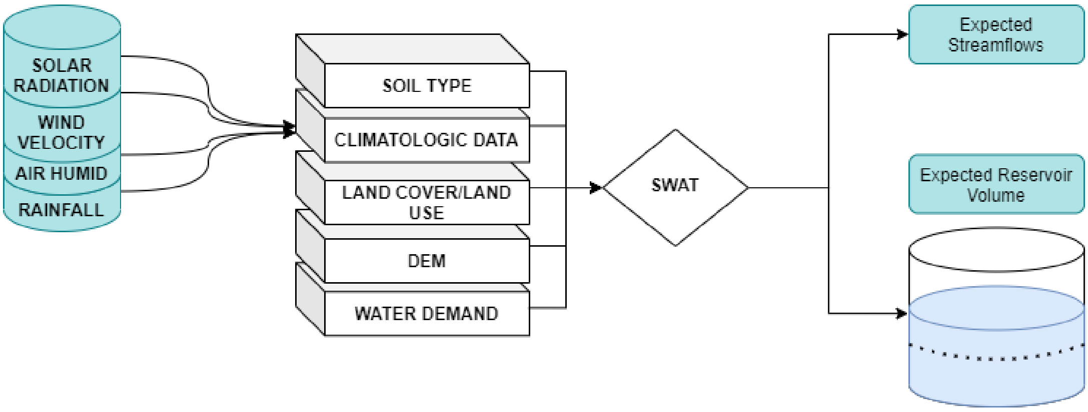

Figure 8-4. Required information for running the SWAT model

During the *Calibrate/Validate step*, the user has to calibrate and validate the model using the SWAT CUP/SUFI-2 coupled with analysis of uncertainties by minimizing deviations based on the Nash-Suttcliffe. This procedure is detailed in Figure 8-5. In the first moment of the calibration phase, the user selects the objective function, decides on a threshold value for best simulation (the default is 0.5), establishes parameters and their respective range values, and defines the number of runs. In the following step, the Latin Hypercube is used to generate random values for the parameters, based on the ranges. SWAT then performs simulations with each set of parameters generated. When this process is complete, SWAT CUP calculates the evaluation criteria (*95PPU*, *NSE*, *PBIAS*, *p-Factor*, *r-Factor*). If the uncertainty criteria are not met, a new iteration should be carried out using a new suggested range supported by the evaluation criteria. At least three iterations are recommended in SWAT Cup and 1000 runs in the SWAT model for each iteration (Abbaspour et al., 2015b) to generate necessary inputs for the next step. Depending on size of the watershed and the volume of data, 500 simulations may be satisfactory (Abbaspour et al., 2015b). When the evaluation criteria are satisfied, the best range is identified for each parameter in the watershed. SWAT CUP will also generate the best parameter values and best simulation. During the validation phase, the same procedure is performed for one iteration where performance of the model is evaluated using independent streamflow data.

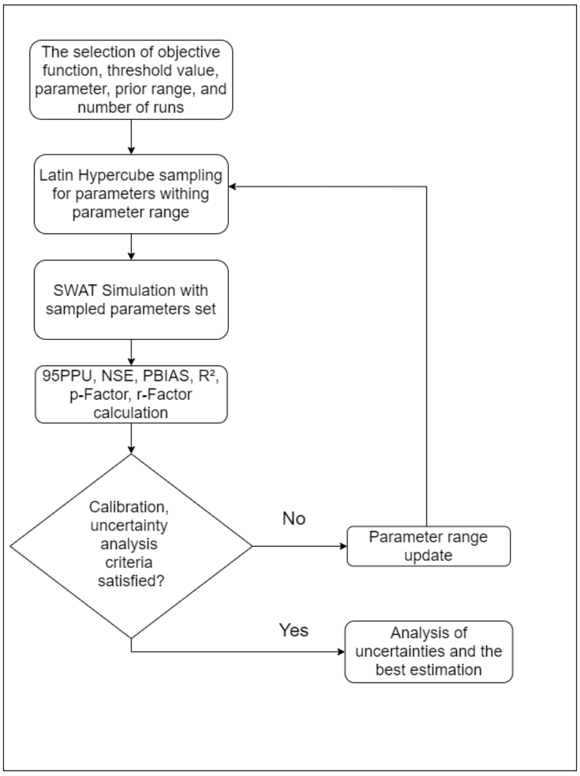

Figure 8-5. The framework of SUFI-2 uncertainty analysis method (adapted from Nunes et al., 2020; Wu and Chen, 2015)

The second step is called *Forecast*. This name implies that following the first step, the prepared model is ready for generating future scenarios. The first step should not be performed again in the future unless significant changes occur in the watershed.

Forecast is divided into three phases: *Selecting Input Data*, *Running Simulation*, and *Dashboards*.

In the *Selecting Input Data* phase, it is necessary to insert climate forecasting data as well as demand and loss information. The user can run the *Forecast* step for different climate and demand data, but it is necessary to run the Forecast step by step for each set of data in order to generate different scenarios as a function of distinct data. This allows for the creation of many scenarios according to the decision-makers' necessities. For instance, if there is the possibility of an increase in water demand and prediction that the amount of rainfall will decrease, the system can create a scenario for each situation or a combined version applying both conditions. These settings can be applied during this step.

The *Running Simulation* phase is divided into four steps. It is initiated by application of an ETL (Extract, Transform, and Load) function. This function is responsible for obtaining selected information, related to rainfall forecasting (Meteorology or stochastic data), and water demands for the *Selecting Input Data* phase, and transforming it into a SWAT input file to be inserted in the "Txt In Out" folder. This folder stores SWAT input files. In the following step, SWAT Cup runs SWAT 1000 times using parameters and ranges acquired in the *Calibrate/Validate* step, generating 1000 simulated streamflows and/or the reservoir volumes. The analysis of uncertainties described in Figure 8-5 is also performed during this step, however just one iteration is executed. Based on this data, the 95 PPU file is created, describing the uncertainty of the model. The variations among simulated streamflows represent expected variation among parameter values, and for each scenario there will be a 95 PPU file because fluctuations related to parameters do not depend on rainfall or water demand.

In the last phase, *Dashboards* can be generated for the main SWAT outputs. This phase makes graphs of forecasted hydrological behavior available to decision-makers. It is possible to view simulated values for reservoir levels and streamflows, based on the different scenarios created by the decision-maker.

8.8. Water Management using InMaS

Operational objectives as described by Salas and Hall (1983) and WMO (2009b) can be summarized as rule curves created to determine reservoir levels where focus is on meeting demands such as fresh water supply, flood control, hydropower, etc. These rules can be developed or supported by mathematical models in order to improve performance (Lund and Guzman, 1999; Nalbantis and Koutsoyiannis, 1997). For water supply, a prudent objective is minimizing or avoiding forecasting shortages by prescribing ideal releases and/or storage levels (Lund and Guzman, 1999).

Rule curves can be used as an important tool for managing water resources as well as communicating to society the current situation related to water storage (Barcellos et al., 2018). Three rule curves were designed during the crisis in the FD based on future scenarios related to the reservoir volumes (Mello et al., 2018). For each curve, restrictions related to withdrawal limits were applied (Mello et al., 2018). The generation of future scenarios presenting variations in water demand, climate variations, or land-use change is an important tool for making robust decisions about water management (Dong et al., 2013). Likewise, the development of reliable rule curves based on those scenarios is strongly dependent on the methodology used (Ahmadi et al., 2010). InMaS expects to assist in generation of these curves, allowing for more realistic predictions supported by two points. First, SWAT is a complex distributed model and makes predictions based on soil moisture conditions, and this type of model is believed to simulate data more closely to reality (Meng and Quiring, 2008). Second, the simulated streamflows present risk analysis based on uncertainties associated with parameters (Abbaspour et al., 2015b) and climate forecasting (Slingo and Palmer, 2011). This process can be seen in Figure 8-6, where the gray area represents possible variations expected in simulated reservoir volume. This is a relevant improvement to the current system employed by ADASA which currently does not allow for risk analysis.

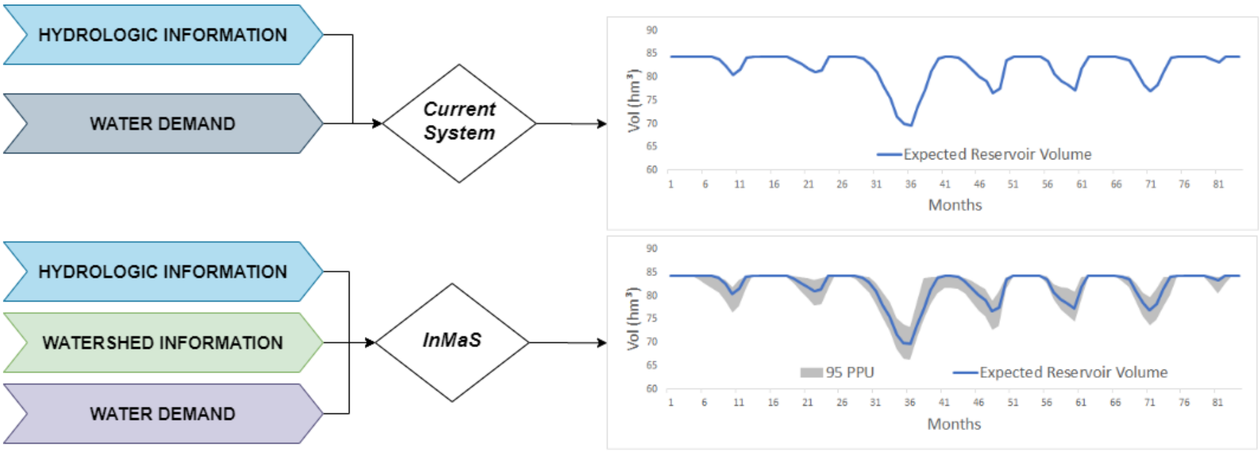

Figure 8-6. Comparison between the current system employed by ADASA and the proposed system (InMaS)

The great advantage of soil moisture models for generation of future scenarios, for instance, is the possibility to assess streamflows based on the current soil situation (Becker and Serban, 1990). Stochastic models use historical data to assess streamflows while deterministic models (a physical soil moisture model in the present case) predict streamflows based on watershed characteristics and climatological conditions (WMO, 2009a). Droughts resulting in amounts of observed rainfall fall below expectations can create difficulties for stochastic models (Pahl-Wostl, 2006). It is expected that the proposed system will remedy this situation, as the SWAT model is highly sensitive to variations in soil water contents and accepts, for example, that current soil moisture levels related to a determined location as limiting factors when generating future scenarios (Neitsch et al., 2011). Moreover, analysis of uncertainties makes it possible to create feasible scenarios and to indicate the likelihood of an event happening, aiding in the decision-making process (Abbaspour, 2015; Mowrer, 2000).

The possibility to analyze hydrological information about the watershed is also offered by InMaS, as depicted in Figure 8-7. Information such as evapotranspiration (Figure 8-7a), baseflow (Figure 8-7b), runoff (Figure 8-7c), percolation (Figure 8-7d), etc. can be offered for all sub-basins within a watershed. Hence, it is possible to assess the impact of changes in land use/land cover across the water yield. Highlighting where actions should be prioritized, the information described in Figure 8-7 can be very useful for decision-makers.

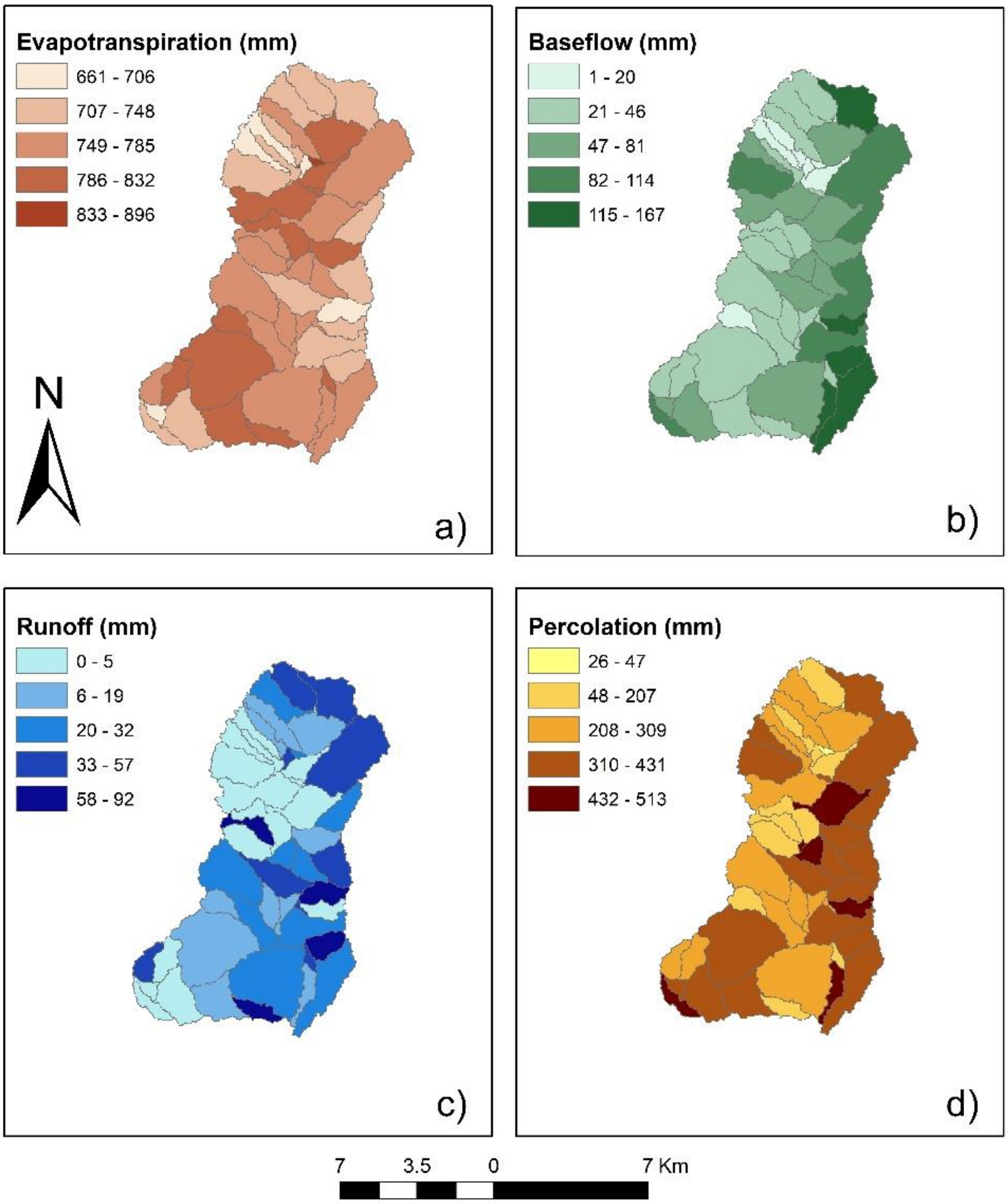

Figure 8-7. Mean Yearly Hydrological information about the watershed. a) Evapotranspiration b) Baseflow c) Runoff d) Percolation

8.9. **Final Considerations**

Several scarcity situations are occurring in many regions of the globe. Brasilia recently experienced its worst drought in its short history. In order to contain this crisis, a simplified management system was developed and obtained good results. However, it lacks more significant hydrological information, such as soil moisture prior to simulation, land use and land cover, and a risk analysis.

In the present work, a DSS was proposed, which aims to add greater reliability to the existing system, using SWAT and SWAT Cup in a coupled manner. To achieve this goal, hydrological information from hydrographic basins, trends in use and occupation of terrain, modifications in the proposed model to be adapted to monsoon regions, in addition to the generation of reliability percentages for the scenarios generated.

As a result, the proposed DSS operation tends to be friendly, respecting local characteristics, allowing the generation of future scenarios, also informing its associated errors.

8.10. **References**

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9. FINAL CONSIDERATIONS

As observed through this research, in many places over the world, it is possible to find water issues, especially related to growing demographic expansion and climate changes. These two points also took place in the Brazilian capital and contributed to a situation of water scarcity in the region. Given this situation, an integrated water resources system plays an important role in water management, helping decision-makers designing and planning future scenarios. The purpose of this research was to develop a decision-making process to help institutions in this process, using SWAT (Soil and Water Assessment Tool), a watershed model, and SWAT Cup (SWAT Calibration and Uncertainty Program), an optimization tool. Integration of both programs associated with a consistent flowchart resulted in InMaS (Integrated Water Management System).

In this research, it was searched shedding a light on the matters of the use of semi-distributed soil moisture models for water management. The SWAT model attends to this requirement and has proven the performance based on literature and results in this research. This type of model allows modeling heterogeneous regions and inclusion of soil moisture conditions. Some difficulties in using the SWAT model in the Federal District, as soil and plant properties, were overcome using a local database generated by deep research of primary data and specific papers developed by the team linked to this project. This is relevant since SWAT demands so much information and many regions do not have it. SWAT Cup is another key point because this program improves the results from modeling and aggregates a risk analysis to them. SWAT Cup also can help to define parameter values, however, actual values always bring more realistic results.

This research was also aimed at allowing the inclusion of variable water consumption data in the use of SWAT for modeling reservoirs. The use of reservoirs needed improvement. This module has been modified to work both daily and monthly, but due to the limited data available, we use it monthly. This addition allows the entire management process to take place within a single modeling program, avoiding bureaucracy and complexities when using more than one platform.

Regarding the hydraulic issue, two changes were made to the SWAT in order to allow greater accuracy in the application of the model in the study region. First, a change in the SWAT’s source code was developed to allow the calibration of the parameters for the SCS Number Curve method. The updating value of the initial abstractions was the focus, which was originally set as constant at 0.2 of S, and the modification allowed a variation according to the land use/land cover. Second, a new equation was created to calculate the groundwater recharge, in which it started to be calculated sinusoidally, according to the drought and rain periods in the region. Such modifications increased the model's effectiveness.

The rainfall variations in the study region were also verified using 21 rain gauges, in which a very large variability was identified spatially and temporally. Rain reduction trends were not significantly identified by the tests used (Mann-Kendal, Wald-Wolfowitz, Spearman, Cox-Stuart). It was also pointed out that the annual variations can make it more difficult to obtain more consistent results, by the tests used. Besides, two SPE (Satellite-derived Precipitation Estimates) products (Multi-Source Weighted-Ensemble Precipitation – MSWEP version 2 and Climate Hazards Group Infrared Precipitation with Station data – CHIRPS) were verified and obtained good performance in the modeling process. CHIRPS obtained a "satisfactory" result during calibration and validation for all objective functions which were used. MSWEP had a similar result, with the exception of the objective function R^2, in which it was classified as "unsatisfactory" in both periods analyzed.

Expansion of water demand, climate variations, and scarcely watershed properties values are key points in water management, and InMaS can contribute significantly to overcome this. Especially when it is compared with the system used currently, where the model is just responsible to analyse the data. The proposed process can generate options and help in decision selection. InMaS gather all this information to provide in one place a suitable program for water management. Also, from water managers perspective, based on our research, three factors can contribute to the distance between science and decision-makers regarding the use of models in water management: the complexity, the non-suitability with local reality, and the lack of political interest. In this study, we deal with the first two aspects, considering as essential requirements for the development of hydrological models: a reliable database and consistency with reality. The managers’ point of view, although subjective, also should be considered when implementing a local model, given that this will be the end-user.

It is recommended for future works:

1 – paying attention to obtaining data about hydrological variables, especially those related to soils, as well as components of land use/land cover and rainwater drainage networks. Soil's properties concerning occupied lands also should be analyzed. Bearing in mind that most of the works carried out in the region, cover few regions and the study area has very heterogeneous characteristics.

2 – checking other satellite data, given the frequent seasonality, as well as a large regional variation, which greatly impacts the modeling of the region.

3 – developing a friendly interface to the InMaS, in order to reduce technological barriers in its operation and become easier its implementation.

Such measures will be fundamental to increase the reliability of predictive models applied in the region, allowing a better analysis of the current scenario, and thus enabling more reliable projections.

Finally, InMaS can become an important program to support water management decisions and the results obtained in this work show the power of such a system in modeling water resources.