Serviço Público Federal
Ministério da Educação
Fundação Universidade Federal de Mato Grosso do Sul
Faculdade de Engenharias, Arquitetura e Urbanismo e Geografia - FAENG

Thamiris Fontoura de Araujo

Assessing hydrological alterations in a tropical basin using an adaptation of the ELOHA framework

Campo Grande, MS
2024

UNIVERSIDADE FEDERAL DE MATO GROSSO DO SUL
FACULDADE DE ENGENHARIAS E ARQUITETURA E URBANISMO E GEOGRAFIA
PROGRAMA DE PÓS-GRADUAÇÃO EM TECNOLOGIAS AMBIENTAIS

Thamiris Fontoura de Araujo

Assessing hydrological alterations in a tropical basin using an adaptation of the ELOHA framework

Dissertação submetida ao Programa de Pós-graduação em Tecnologias Ambientais da Universidade Federal do Mato Grosso do Sul como requisito para a obtenção do título de Mestre em Tecnologias Ambientais. Área de concentração: Saneamento Ambiental e Recursos Hídricos.

Orientador: Prof. Dr. Paulo Tarso Sanches de Oliveira

Aprovada em: 11 de março de 2024

Banca examinadora:

Prof. Dr. Paulo Tarso Sanches de Oliveira
Orientador
PGTA- UFMS

Dra. Gabriela Chiquito Gesualdo
Pennsylvania State University

Dra. Angélica Guerra
Instituto Terra Brasilis

Campo Grande, MS
2024

To God, the divine source of my strength and the guide of my path. To my dear parents, Adélia and Iolando, as well as my sister, Thainara, for their support and contributions that enabled the completion of this work.

ACKNOWLEDGEMENTS

First, I would like to thank my parents and sister for the support, love, and patience in all my life. Especially, I would like to thank my aunt Valéria and my friends Bruna, Carolina, Thiago, and Katia, who always believed, supported, helped, and took care of me. You all were by my side at tough times and believed in me even when I felt I couldn’t make it.

To my advisor, Prof. Dr. Paulo Tarso Sanches de Oliveira, who is a great inspiration and supporter. Thanks for the orientation, support, availability, and patience during this long journey. To Dr. Jullian Sone, my friend and one of the smartest and coolest person I have ever met. Thank you so much for our always productive conversations and for teaching me so much over these years. I feel truly grateful that I have had the opportunity to work with people who always want to share knowledge, are so open-hearted, and have no selfishness.

To my colleagues in the Hydrology, Erosion and Sediment Laboratory (HEroS) and Hydrology and Water Security research group (HWS), especially Msc. Camila Couto, Dr. Gabriela Gesualdo, Dr. Glauber Altrão, Msc. Juliene Gonçalves de Almeida Garcia and Prof. Dr. Teodorico Alves Sobrinho for the insights, partnership, and shared experiences. Finally, I would like to thank the Federal University of Mato Grosso do Sul and the Graduate Program in Environmental Technologies for the support during this period and to Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the financial support at the first stage of this research.

This project was supported by Federal University of Mato Grosso do Sul Foundation – UFMS/MEC – Brazil.

ABSTRACT

ARAUJO, T. F. (2024). Assessing hydrological alterations in a tropical basin using an adaptation of the ELOHA framework. 2024. 71 p. Dissertation (Master) – Graduate Program in Environmental Technologies. Federal University of Mato Grosso do Sul, Brazil.

A better understanding of the interplay between ecological responses, climate variability, and water resources management provides a robust resource for policymakers in refining environmental flow targets. However, studies encompassing streamflow alterations and their impacts on environmental flow targets are still scarce in many countries, especially under climate change scenarios. Here, the impacts of climate change on streamflow in a tropical watershed covering 362 km² in midwestern Brazil, which supplies water to nearly 34% of the approximately 900 thousand inhabitants, were investigated using an adapted version of the Ecological Limits of Hydrologic Alteration (ELOHA) framework. The hydrological physically based SWAT+ model was used and calibrated to simulate the watershed's hydrological response to three climate change scenarios from the seven General Circulation/Earth System models (GCM/ESM) provided by the Coupled Model Intercomparison Project phase 6: SSP2-4.5 (moderate forcing), SSP3-7.0 (moderate to high forcing), and SSP5-8.5 (high forcing). The SSP2-4.5 and SSP3-7.0 exhibited the greatest hydrologic alterations in the median flows from 2015 to 2100, reaching a high alteration degree of 0.71 and 0.67, indicating higher frequency in high flow values; the SSP5-8.5 and baseline are mostly alike in terms of median flows despite the hydrologic alteration reaching a moderate alteration degree of -0.51. The findings show an increasing trend in median flow over the future period in the three scenarios due to an increase in the frequency of extreme flood events. The SSP5-85 exhibited the most vulnerability to an extreme low flow event. It was observed an average of 142 (SSP2-4.5), 150 (SSP3-7.0), and 136 days (SSP5-8.5) of low precipitation (< 1mm) to trigger periods of extreme low flow, which are streamflow values lower than 10% of daily flows for the period on the basin. According to the scenarios, shifts in hydrological frequencies showed a stronger correlation to precipitation patterns than to evapotranspiration. The hydrological shifts in the frequency of floods and droughts impacts on the life cycles of species, community diversity, and habitat conditions (including temperature, dissolved oxygen levels, and accessibility for aquatic and terrestrial species). Moreover, these changes have significant implications for water service management, requiring continuous revisions of water plans and regulations due to the variability in the streamflow and water quality. This study also highlights the challenges of fully implementing the framework in Brazil, as well as emphasized the importance and the need of similar research to enhance water resources management and decision making, mainly in the context of water insecurity.

Keywords: Hydrological Changes; Water supply; Future Projections.

RESUMO

ARAUJO, T. F. (2024). Assessing hydrological alterations in a tropical basin using an adaptation of the ELOHA framework. 2024. 71 páginas. Dissertação (Mestrado) - Programa de Pós-graduação em Tecnologias Ambientais. Universidade Federal de Mato Grosso do Sul, Brasil.

Uma compreensão mais profunda da interação entre as respostas ecológicas, a variabilidade climática e o gerenciamento dos recursos hídricos fornece uma base sólida para os formuladores de políticas refinarem metas de vazão ambiental. No entanto, estudos abrangendo alterações no fluxo dos cursos d'água e seus impactos nas vazões ambientais ainda são escassos em muitos países, especialmente sob cenários de mudança climática. Neste trabalho, os impactos das mudanças climáticas na vazão dos cursos d'água em uma bacia tropical que abrange 362 km² no centro-oeste do Brasil, abastecendo água para quase 34% dos aproximadamente 900 mil habitantes, foram investigados usando uma versão adaptada do framework Ecological Limits of Hydrologic Alteration (ELOHA). O modelo hidrológico baseado em princípios físicos, SWAT+, foi usado e calibrado para simular a resposta hidrológica da bacia aos três cenários de mudança climática dos sete modelos do General Circulation/Earth System (GCM/ESM) fornecidos pelo Coupled Model Intercomparison Project phase 6: SSP2-4.5 (forçamento moderado), SSP3-7.0 (forçamento moderado a alto) e SSP5-8.5 (forçamento alto). O SSP2-4.5 e o SSP3-7.0 apresentaram as maiores alterações hidrológicas nas vazões medianas de 2015 a 2100, alcançando um grau de alteração alto de 0,71 e 0,67, indicando maior frequência em valores de vazões altas; o cenário SSP5-8.5 e a base histórica são em sua maioria semelhantes em termos de vazões medianas, apesar da alteração hidrológica atingir um grau de alteração moderado de -0,51. Os resultados mostram uma tendência crescente nas vazões medianas ao longo do período futuro nos três cenários devido a um aumento na frequência de eventos de inundação extrema. O SSP5-8.5 mostrou a maior vulnerabilidade a um evento de vazão extremamente baixa. Observou-se uma média de 142 (SSP2-4.5), 150 (SSP3-7.0) e 136 dias (SSP5-8.5) de baixa precipitação (< 1 mm) para desencadear períodos de vazão extremamente baixa, que são valores de vazão inferiores a 10% dos valores diários para o período na bacia. De acordo com os cenários, as mudanças nas frequências hidrológicas mostraram uma correlação mais forte com os padrões de precipitação do que com a evapotranspiração. As mudanças hidrológicas na frequência de enchentes e secas impactam nos ciclos de vida das espécies, na diversidade da comunidade e nas condições do habitat (incluindo temperatura, níveis de oxigênio dissolvido e acessibilidade para espécies aquáticas e terrestres). Além disso, essas mudanças têm implicações significativas para o gerenciamento dos serviços de distribuição de água, exigindo revisões contínuas de planos e regulamentos devido à variabilidade no fluxo dos cursos d'água e na qualidade da água. Este estudo também destaca os desafios de implementar completamente o framework no Brasil, bem como enfatiza a importância e a necessidade de pesquisas semelhantes para aprimorar o gerenciamento dos recursos hídricos e a tomada de decisões, principalmente no contexto da insegurança hídrica.

Palavras-chave: Mudanças Hidrológicas; Abastecimento de Água; Projeções Futuras.

LIST OF FIGURES

LIST OF TABLES

CONTENTS

1. INTRODUCTION

Understanding the seasonality of the basin's flow and its ecological consequences plays an important role in water management and security. Leroy Poff et al. (1997) established a direct link between flow dynamics and the ecological integrity of river ecosystems. Meanwhile, there is evidence indicating that climate change significantly influences flow alterations (MILLY et al., 2008). Besides that, there is a considerable number of studies that try to model streamflow under future scenarios to investigate trends and potential flow alteration (e.g., Arias et al. (2020), Gudmundsson et al. (2021)). According to Karr (1991) and Leroy Poff et al., (1997) the ecological changes of a river are directly and indirectly dependent on interactions among the five components of the flow regime (i.e., magnitude, frequency, duration, timing and rate of change) and their responses to initial regulators. Studies as Gibson et al. (2005), Pérez-Sánchez et al. (2020) and Wang et al. (2016) assessed climate change impacts on water flows and ecological alteration patterns using tools to describe floods and high and low flows. However, there is still a lack of ecological data from river basins responsible for water supply to support and inform studies on ecological responses. Indeed, water regulatory authorities in certain nations, particularly Brazil, do not consider ecological evidence to regulate minimum flows because of (but not only) a lack of data. In places where ecological data are absent, is still possible to engage in discussions on potential water flow/ecological response relationship aiming at the enhancement of environmental flow characterization for stakeholders and water managers in the future.

Collective social-ecological research in partnership with governing bodies could foster a shared vision of regional sustainability to advance feedback loops between human activities and water-ecosystem functioning (MAASS et al., 2005). This cooperation is of paramount importance for building a framework to effectively tackle both society and environmental needs and challenges. Water management frameworks can emerge as effective tools in establishing environmental flow standards at a regional scale; however, gathering information within a scheme that can be adapted to other study cases is a challenge (ARTHINGTON et al., 2006; POFF et al., 2003). Acreman, Ferguson (2010), Dearing et al. (2014), Felipe-Lucia, Comín, Escalera-Reyes, (2014) and O'Brien et al. (2018) have employed frameworks to investigate social and economic processes, as well as the water flow information mentioned earlier on a regional scale. These framework studies aimed at guiding and ensuring a sustainable future for society, ecosystems and freshwater supply.

A group of scientists decided to join expertise and knowledge to build a framework named Ecological Limits of Hydrologic Alteration (ELOHA, (Poff et al., (2010)). This structure contributes to scientists, stakeholders and water managers to investigate and define goals for environmental flows considering river basins' ecological and social information (POFF et al., 2010). This framework has been used for many years as a tool for water management in several case studies such as in the Colorado River basin, Middle Potomac River basin, Australian Legal Water Reforms, and the Madalena River basin in Colombia (The Nature Conservancy, 2023). Studies were also conducted worldwide (e.g., Buchanan et al. (2013), Capítulo et al. (2022), Némethy et al. (2022)). These studies applied the ELOHA framework in different contexts to help water managers in the United States of America, Argentina and Europe. Specifically, studies in Europe (KURIQI et al., 2019) and in Ethiopia (ABEBE et al., 2022) focused on comparing Environmental Flows methodologies, including the ELOHA, to enhance local water policies. In Brazil, few studies adopting ELOHA framework are noticed (e.g., as in SiddiquI et al., (2021)). There are social and environmental needs to explore and improve research around Environmental flows, river flow patterns and hydrology in general.

Additionally, an urgency for ecological monitoring stations and investments over water-socio-ecological methodologies are required, due to the lack of hydrological and ecological data, lack of adaptation or development of Environmental Flow Methods (REITBERGER; MCCARTNEY, 2011). Brazil's water manager institutions, as well as the case study in Ethiopia (ABEBE et al., 2022), apply methods that consider only exceedance probability flows (e.g., Q_{95}, Q_{90}, $Q_{7,10}$). Thus, ELOHA methodology holds significant potential for informing water policies in Brazil as it provides user-friendly features and takes into account not only river flows, but social and ecological processes, such as management requirements and social values balanced to meet acceptable ecological conditions.

Brazil is one of the richest countries when it comes to water, even richer in terms of ecological diversity. Therefore, studies on water have been developed throughout the country and, consequently, ecological and climate change studies as there is a strong relationship between the subjects. As global temperature rises, changes in the hydrological cycle become more pronounced, leading to significant shifts in the magnitude, frequency, and intensity of extreme events such as droughts and floods (CHAGAS; CHAFFE; BLÖSCHL, 2022; GITHUI et al., 2009). Furthermore, these changes are projected to intensify throughout this century (IPCC, 2023; MULLAN; FAVIS-MORTLOCK; FEALY, 2012; WIGLEY; RAPER, 2001), particularly in vulnerable regions like Brazil (e.g., Dos Santos et al. (2020), Gesualdo et al. (2021), Hegerl et al. (2004), Magrin et al. (2014)). Streamflow alteration in the Cerrado (Brazilian savanna) under current and climate change scenarios has been studied in the last years (e.g., Dias et al., 2015; Nóbrega et al., 2017; Rodrigues et al., 2020; Sone et al., 2022; Spera et al., 2016). The basins' streamflow is decreasing and becoming a risk for water supply and ecosystem maintenance; cities are therefore using groundwater as an alternative for human consumption. However, studies such as Neto et al. (2021) showed that not only superficial but also groundwater in the Cerrado may suffer impacts on water availability as a result of changes in the precipitation and temperature patterns. These impacts highlight the necessity to enhance decision-making processes at a basin scale, instead of solely seeking alternative sources such as groundwater.

In this context, the objective of this study is to characterize shifts in flow regimes due to climate change in the Guariroba River basin to gain insights on possible ecological responses using an adaptation of the ELOHA framework. Exploring hypothetical climate change scenarios through studies can provide important insights for basin management and decision-making. These scenarios enable the assessment of potential measures to mitigate environmental damage in the region, such as implementing conservation practices or establishing environmental flow for both dry and flood seasons. We used a statistically downscaled and bias-corrected ensemble of seven General Circulation/Earth System models (GCM/ESM) within the Coupled Model Intercomparison Project phase 6 (CMIP6) provided by Sone et al. (2022). By exploring potential ecological responses, our findings provide potential solutions to stakeholders and water managers. Likewise, the aim is to enhance the comprehensive characterization of the basin over the years, corroborating the previous studies carried out in the Guariroba basin and improving decision-making to tackle the negative impacts of both droughts and floods in the future.

2. GENERAL OBJECTIVES

The objective of this study is to assess streamflow alteration due to climate change scenarios in a tropical river basin.

2.1. Specific objectives

i. To quantify and characterize hydrological shifts and alteration in streamflow regimes under three climate change scenarios: SSP2-4.5, SSP3-7.0, and SSP5-8.5.

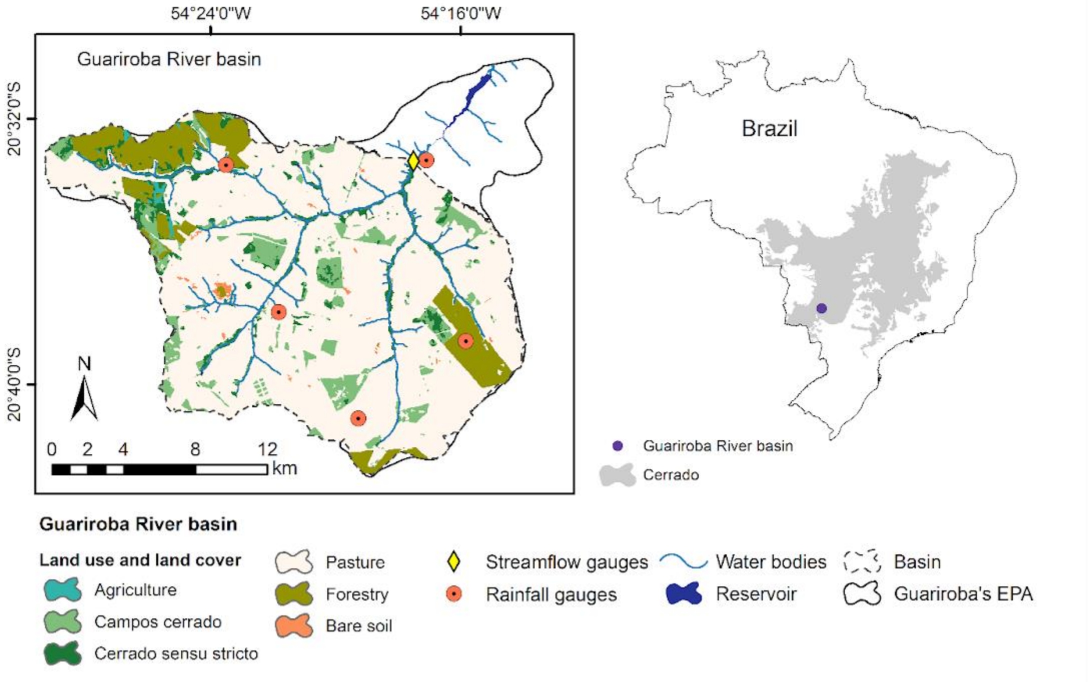
ii. To identify and suggest actions for water management considering the basin water demands.

3. MATERIAL AND METHODS

3.1. Study Area

This study was carried out in the Guariroba river basin, an important basin that currently supplies water to nearly 34% of the approximately 900 thousand inhabitants of Campo Grande, Mato Grosso do Sul, Brazil (Figure 1). This basin has 362 km² and is located in the Cerrado biome. With significant agricultural practices prevalent in the region, without the use of good practices and soil management and considering the impact of climate fluctuations, it is anticipated that water availability could experience further decline (SONE et al., 2022).

Figure 1. The Guariroba River Basin location in Cerrado Biome, characteristics, and monitoring locations. Land use and land cover from 2018 (Mapbiomas Project, 2019) were used in this study.



Source: Author.

According to the Köppen classification, the climate in this area is classified as humid tropical (Aw), featuring an average temperature of 23.4 ºC and an average annual precipitation of 1449 mm and characterized by dry winter from June through September and rainy summer from December through March. The predominant soil classes in the basin are Quartzarenic Neosols (93.5%), Hydromorphic Neosols (3.5%), and Red Latosols (3%). The basin area has an average relief slope of 3.7% and sandy soils with high water infiltration rates (VALLE JUNIOR, OLIVEIRA, RODRIGUES 2019), although there is a need to observe degradation risk by water erosion due to basins' soil characteristics.

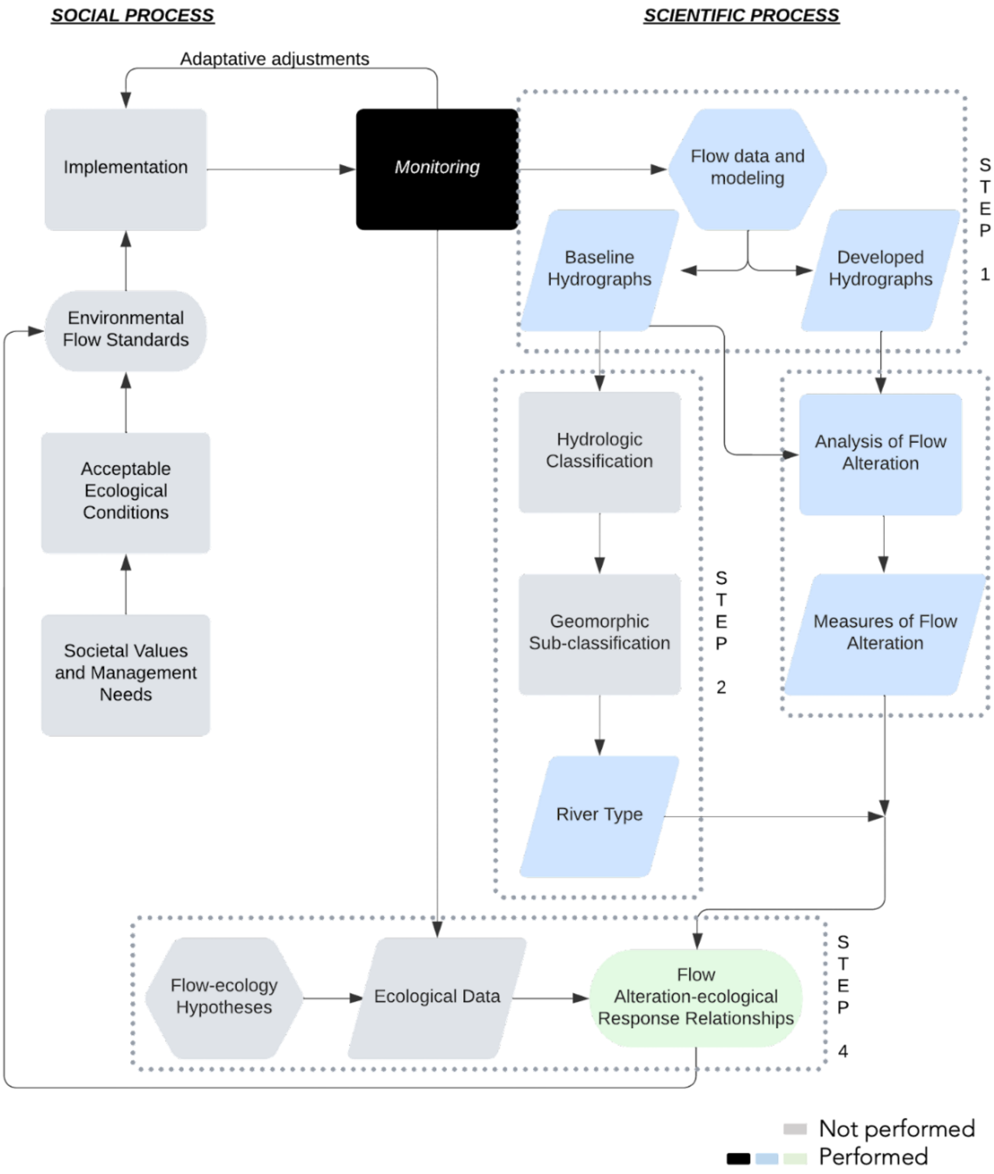
Guariroba river basin is composed by 5 sub-basins, and 73.8% of the total area is used to agricultural production with established pasture, nevertheless there are also other types of occupation as native Cerrado vegetation (15.2%), eucalyptus (10.1%), non-vegetated area (0.5%) and agriculture (0.3%) (Mapbiomas Project, 2019). In recent years this basin has lost soil by erosion at high rates due to deforestation on Permanent Preservation Areas and native vegetation areas replaced by agricultural activities. In 1995, Guariroba basin was designated as an Environmental Protection Area (EPA); then, the city hall implemented a Payment for Environmental Services program called "Manancial Vivo" in 2009 due to its level of degradation and relevance for water supply. The program aims at improving water infiltration into the soil and biodiversity preservation and decreasing soil losses by implementing conservation practices, such as building level terraces and fencing native forest and riparian areas. The program contributed to implementing soil and water conservation practices, maintaining local roads, building animal watering facilities, and promoting environmental education. Thereby, economic incentives were provided to farmers who have implemented and maintained the practices. This program has contributed to an increase in water yield (SONE et al., 2019), alleviating the impacts of severe events such as droughts.

3.2. ELOHA Framework

Ecological Limits of Hydrologic Alteration – ELOHA is a framework that involves a number of steps using environmental flow techniques and methods to support flow management by considering ecological and social interference in the process (POFF et al., 2010). In the last years, several studies aiming at informing decision-making and water resources management at a basin scale have used the ELOHA Framework worldwide, including countries such as China (ZHANG et al., 2012), Australia (MACKAY; ARTHINGTON; JAMES, 2014), Spain (BELMAR; VELASCO; MARTINEZ-CAPEL, 2011), Colombia (CUÉLLAR and NEIRA, 2014) and USA (MARTIN; LABADIE; POFF, 2015), for instance.

ELOHA consists of two parts, the scientific and social processes (Figure 2). In this study the focus is mainly on the first part, but also in to incorporate the social drivers influencing our results by discussing possible social and hydro-ecological interactions and feedback loops. Is not possible to incorporate the social part according to the original framework because there is no socio-ecological data available for the study area, as well as limited observed hydrological data throughout the basin. Even so, the ELOHA framework provides key hydrological signatures, allowing insights to be gained to inform decision-makers of relevant ecological implications and, therefore, enhance water security within and beyond the basin’s boundaries. Thus, here is an adaptation of the original framework, which now consists of the following steps (blue and green steps illustrated in Figure 2): (i) Hydrologic foundations; (ii) River classification; (iii) Flow alteration; and (iv) Flow-ecology linkages. A summarized overview of the scientific steps undertaken is provided below. Further, comprehensive details on these steps can be found in the subsequent sections of this work.

Figure 2. ELOHA Framework and its adapted version following items from the Scientific Process. The steps taken in this study are colored in black, blue and green.

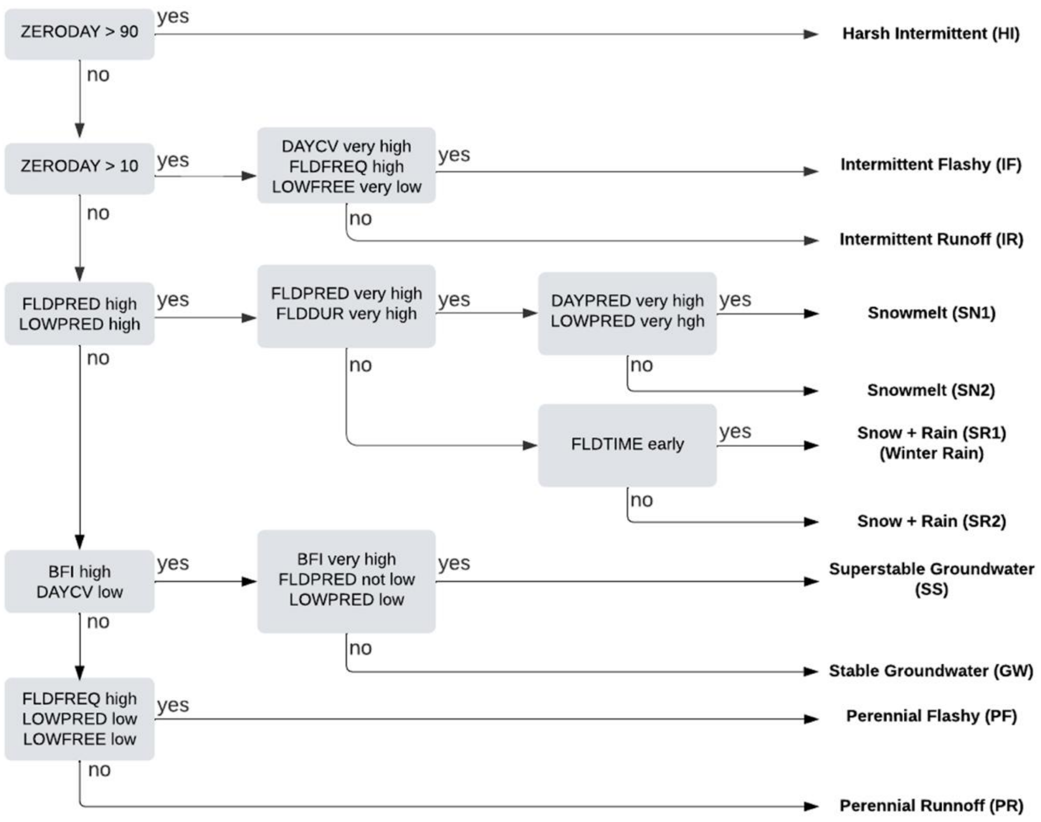


Source: Adapted from Poff et al. (2010)

The first step involves using historical river flow data and building future scenarios to make an appropriate discussion of possible future social-ecological challenges (pre- and post-impact assessment). This impact assessment was based on three Shared Socioeconomic Pathways (SSPs) simulated by seven General Circulation/Earth System models (GCM/ESM) within Coupled Model Intercomparison Project phase 6 (CMIP6) from 2015 to 2100. Here, the historical simulations (1980-2014) are compared to a multimodel ensemble provided by Sone et al. (2022). The climate change data were used as input in the SWAT+ model, detailed in section 3.2.1.

River classification is part of the second step, which classifies every river in the basin according to its characteristics. As there is not enough data available for the tributaries and upstream the main monitoring gauge at the Guariroba's lower course, right before the reservoir (see Figure 1), the river network is classified based only on the main river, delimited by the lower course's gauge, as perennial stable groundwater using the Poff's (1996) guidelines (Figure 3). Our classification took into account the zero day with no flow (ZERO DAY), low coefficient of variation (DAYCV), very high baseflow index (BFI, based on the study of Sone et al. (2019)), and low seasonal predictability of floodings (FLDPRED) and low flows (LOWPRED). In the case of the ZERO DAY criterion, it is computed when no more than 10 days with no water flow is observed. Nonetheless, river classifications become necessary solely when examining each individual river and tributaries within the basin. The river classification plays an important role when analyzing multiple rivers in the same basin, enabling analogies between each type of river. The inability to conduct such analysis in the Guariroba basin highlights the necessity for investments across the entire river network, collecting data and treating each particularity of the rivers as integral components of the network.

Figure 3. Poff's flowchart for individual stream classification according to the stream magnitudes characteristics such as zero-flow days, coefficient of variation, baseflow index, floodings predictability and low flows predictability.



Source: Adapted from Poff (1996)

In the third step, flow alteration was computed using the Indicators of Hydrologic Alteration (IHA) software version 7.1 (The Nature Conservancy, 2009). This software allowed us to estimate parameters (e.g., median flows for each month of the year, moving averages for maximum and minimum flow, baseflow index and number of zero days) and Environmental Flow Components (EFCs) for the pre- and post-impact assessment. The elaboration of the remaining aspects of this step is presented in section 3.2.2. In addition to the identification of flow alterations, further descriptions of flow-ecology linkages (ecological responses, according to flow alteration) were provided. Arthington et al. (2006) showed that flow alteration and ecological responses can have endless relationships, including effects on species diversity, biomass, community composition, flood extent, and the diversity of aquatic habitat. Indeed, ecology responses may vary (positively or not) according to the river degree of alteration. Given the absence of ecological data in this study, our focus was to demonstrate categorical and trajectory relationships in order to provide information and support decision-making such as in Arthington et al. (2003), King; Brown (2006), Shafroth et al. (2010).

3.2.1. Hydrologic Foundation

To simulate the Guariroba River Basin's hydrological response to three climate change scenarios, we used the SWAT+ model (revision 59.3), previously calibrated and evaluated by Sone et al. (2022). This model was used in other studies, and its principal application is in hydrological processes associated with different land uses, soil management, and climate change (GASSMAN; SADEGHI; SRINIVASAN, 2014). The SWAT+ (BIEGER et al., 2017) is a physically based and semi-distributed model usually applied in small and large basins to simulate water and sediments flows. SWAT+ uses a QGIS interface (QSWAT) and makes spatial representation and hydrological processes more flexible by introducing the landscape units (LSU), which separate the lowland from upland processes. In the model, the water balance drives the hydrological processes, and water storage takes place through the soil layers and shallow and deep aquifers.

Subbasins were divided into lumped hydrologic response units (HRUs), with a homogeneous combination of land use, soil, and slope. These HRUs were delineated considering a threshold of 20% for land use and 10% for soil order and slope as recommended by Jha (2011). Further detail about the source of input data, calibration and validation can be found in the Supplementary Material of Sone et al. (2022). Lateral flow travel time (LAT_TTIME), slope length for lateral subsurface flow (LAT_LEN), percolation coefficient (PERCO), and the soil hydraulic conductivity (K) exhibited a higher sensitivity in the model. The model evaluation analysis showed a satisfactory correlation (Pearson correlation coefficient (r) of 0.74), with a Kling Gupta efficiency (KGE) of 0.72 and 0.68 for the calibration and evaluation periods, respectively. The model's performance is suitable considering that reanalysis data were used to fill the gaps in the observed streamflow records. Percent bias in the evaluation period indicates a slight underestimation (-3.4%), comparing the calibration with the evaluation period. Taking into account the quality of the observed data regarding the number of gaps.

To assess climate change impacts on water flow regimes from 2015 to 2100, we used the climate change scenarios data from a statistically downscaled and bias-corrected ensemble of seven General Circular and Earth System models (GCMs/ESMs) within the Coupled Model Intercomparison Project phase 6 (CMIP6) (Eyring et al. 2016) of the Intergovernmental Panel on Climate Change (IPCC). The seven GCMs used in this study to compute the ensemble were chosen based on the availability of variables (precipitation, temperature, windspeed, relative humidity and surface net downward shortwave radiation) required to set and calibrate the SWAT+ model (Table 5 in the Appendix). We also limited the nominal resolution of the GCMs/ESMs up to 100 km. The ensemble is also provided by Sone et al. (2022) and is composed of the models described in Table 6 in the Appendix.

The multimodel ensemble alone showed an underestimation of extremes, particularly for precipitation. Despite addressing intrinsic errors in models, downscaling is recommended for regional studies since even ensembles of GCMs/ESMs can poorly perform due to their coarse spatial resolution. Thus, a first-order remapping was carried out to standardize the resolution of all seven models to 2.0° x 1.5° to construct the ensemble. Then, a multi-model ensemble regridding was realized to match the spatial resolution of Xavier's dataset (0.25° x 0.25°) (XAVIER; KING; SCANLON, 2016). A bias correction of all climate variables was also performed, involving the detrending of the multimodel ensemble outputs and applying the quantile mapping method to the series (CANNON; SOBIE; MURDOCK, 2015).

Three climate change scenarios were adopted and analyzed in three 30-year periods as (i) immediate future (2015-2040), (ii) intermediate future (2041-2070), and (iii) distant future (2071-2100). The three scenarios are based on the Shared Socioeconomic Pathways (SSPs) (O'NEILL et al., 2016, 2017), which consider greenhouse gas emissions and changes in Earth's radiation balance, and it represents future socioeconomic projections and the political context (GIDDEN et al., 2019): (i) the SSP2-4.5 is also called "middle of the road" and is a medium scenario, moderate population growing, intermediate societal vulnerability and medium forcing level category (4.5 W.m^{-2} in 2100); (ii) SSP3-7.0 or "regional rivalry" is a medium to high development scenario, with changes in soil use due to continuous deforestation, rapid agriculture expansion and high climate forcing emissions (7.0 W.m^{-2} in 2100); and (iii) SSP5-8.5 is also called "fossil fueled development" and considers a high world development using the highest emissions that can produce radiative forcing of 8.5 W m^{-2} in 2100.

3.2.2. Flow Alteration and Flow-Ecology Linkages

Flow alteration comprehension depends on several factors which includes statistical data analysis, pre- and post-impact comparison, and flow parameters. To calculate characteristics of baseline (considered the historical climate simulations) and altered river flows (based on the three climate change scenarios), we used the Indicators of Hydrological Alteration software (IHA) (The Nature Conservancy, 2009). The IHA software calculates 67 statistical parameters where 33 describes IHA parameters and 34 describes EFCs parameters.

IHA parameters are divided into 5 groups and their ecological implications are described in Table 7 in the Appendix. Group 1 is composed of the median monthly flows. Group 2 is made of zero flow days, base flow indices and extreme flow regimes according to the following moving averages in each year period: 3, 7, 30, and 90-day minimum and maximum flows. Besides, 1-day minimum and maximum flows are also computed and respectively represent the lowest and the highest single-day value occurring during a certain year. Group 3 represents the Julian day in which the extreme water condition first occurred. In other words, if there are multiple days in a year with the same minimum or maximum flow value, the first date is recorded. Group 4 describes high and low pulses, which are values greater than or less than a threshold (median plus or minus 25 percent). In this study, all flows greater than 7.97 m^3/s, less than or equal to 6.58 m^3/s, and less than or equal to 4.71 m^3/s were classified as high, low, and extreme low flows, respectively. Small floods are all high flow events that have a peak flow between 14.65 and 19.10 m^3/s (i.e., 14.65 small flows **<** 19.10). High flow pulses are those events with a peak flow less than 14.65 m^3/s while large floods events are those with a peak flow greater than or equal to 19.1 m^3/s. It is important to note that these thresholds are calculated using data exclusively from the pre-impact period. Lastly, Group 5 consists of reversals, which describe periods where daily changes in flows are either positive or negative (i.e., rising and falling periods). Parameters in Group 5 are calculated using the median of positive (rising rates) and negative differences (falling rates) and the number of times that the flow switches from rising to fall rates (reversals).

A set of 33 IHA parameters provides insights to discuss water resources management and inform policymaking. In this study, the focus is only on parameters that describe extreme flow regimes impacted by climate change (e.g., as in Gibson et al. (2005)). The whole set of 33 parameters aims at analyzing differences in river flow regimes from established pre- to post-impact periods usually caused by dams. Therefore, our analysis is based only on parameters in Groups 1 and 2 (Table 1), which better reflect changes in extreme flow regimes triggered by climate. Detailed information about the other IHA parameters, which have been organized into five distinct groups, can be found in the Appendix.

Table 1. IHA parameter groups considered in this study (originally there were 5 groups), the parameter description of each group and their possible ecosystem influences in the environment. Group 1 considers 12 parameters (representing each month of the year).

IHA Parameter Group	Hydrologic Parameters	Ecosystem Influences
1. Magnitude of monthly water conditions	Mean or median value for each calendar month	· Habitat availability for aquatic organisms · Soil moisture availability for plants · Availability of water for terrestrial animals · Availability of food/cover for furbearing mammals · Reliability of water supplies for terrestrial animals · Access by predators to nesting sites
	Subtotal 12 parameters	· Influences water temperature, oxygen levels, photosynthesis in water column
2. Magnitude and duration of annual extreme water conditions	Annual minima, 1-day mean Annual minima, 3-day means Annual minima, 7-day means Annual minima, 30-day means Annual minima, 90-day means	· Balance of competitive, ruderal, and stress- tolerant organisms
	Annual maxima, 1-day mean Annual maxima, 3-day means Annual maxima, 7-day means Annual maxima, 30-day means Annual maxima, 90-day means	· Creation of sites for plant colonization
	Number of zero-flow days	· Structuring of aquatic ecosystems by abiotic vs. biotic factors
	Base flow index: 7-day minimum flow/mean flow for year	· Structuring of river channel morphology and physical habitat conditions
		· Soil moisture stress in plants
		· Dehydration in animals
		· Anaerobic stress in plants

		· Volume of nutrient exchanges between rivers and floodplains · Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments · Distribution of plant communities in lakes, ponds, floodplains
	Subtotal 12 parameters	· Duration of high flows for waste disposal, aeration of spawning beds in channel sediments

Source: The Nature Conservancy (2009)

For pre (baseline from 1984 to 2010) and post impact (scenarios from 2015 to 2100) assessment, the Range of Variability Approach (RVA) was adopted, which are boundaries to define categories in pre impact period and apply later for post impact period analysis. The assessment seeks to maintain the distribution of the annual IHA parameters as similar as possible to pre-impact distributions. Therefore, RVA uses the baseline data as a reference to limit the degree of change of natural flow patterns and could also be defined as a target for the post impact period. The RVA assessment numerically gauges the extent of modification (Hydrologic Alteration - HA) in Groups 1 and 2 flow parameters and is represented by Equations 1 and 2 (RICHTER et al., 1997).

$$HA = (Of - Ef) / Ef \qquad \text{Eq. 1}$$

where HA (dimensionless) is the Hydrologic Alteration, Of is the observed frequency and Ef is the expected frequency as:

$$Ef = PrO * NPr / NPo \qquad \text{Eq. 2}$$

where Ef is the expected frequency, PrO is the pre-impact number of occurrences in the category, NPr is the number of pre-impacted years and NPo is the number of post-impacted years. Every parameter from the pre impact period is allocated in three categories (RVA boundaries) — low, middle and high — of equivalent sizes based on percentiles. The low category presents all median flow values less than or equal to the 33rd percentile. The middle category presents all median values in the range of the 34th to 67th percentiles, and the highest category comprises all median records exceeding the 67th percentile. After calculating the expected frequency in the post impact period for each category, the frequency of each post-impact annual values of IHA parameters are then computed. Positive HA occurs when the frequency within a category increases from the baseline period to the scenarios period. Conversely, negative HA indicates a decrease in frequency, with a minimum value of -1. Richter et al. (1998) defined three classes of Hydrological alteration degrees which are: (i) small or no alteration (0.0-0.33 HA); (ii) moderate alteration (0.34-0.67 HA); and high alteration (0.68-1.0 HA).

To complement the analysis, the Environmental flow components (EFC) and their descriptions for Ecosystem Influences (Table 8 in Appendix) was used. EFC were added to the IHA software to assist in the interpretation of hydrological events such as floods and droughts (The Nature Conservancy, 2009). Environmental Flow Components are 5 different ecologically relevant categories to uphold preservation of the ecological health of riverine environments. Such categories established within thresholds in IHA software properties are described in Table 2.

Table 2. The Environmental Flow Components (EFC) description. These characteristics allow the IHA software to run the input data and separate each component.

Category	Description
Extreme low flows	Initial low flows lower than 10% of daily flows for the period.
Low flows	All flows lower than 50% of daily flows for the period.
High flow pulses	All flows that exceed 75% of the daily flows for the period. It starts when flow increases by more than 25% per day and ends when flow decreases by less than 10% per day.

Small floods	An initial high flow with a peak flow greater than 2 years of return interval event.
Large floods	An initial high flow with a peak flow greater than 10 years of return interval event.

The IHA software computes EFC parameters; however, conducting RVA analysis on the EFC parameters is unfeasible (RICHTER et al., 1997). It is also not recommended to compare pre-impact EFC with post-impact EFC parameters because the IHA software re-assigns daily flow values into distinct EFC categories, making it inappropriate to directly compare post-impact EFC magnitude values with their pre-impact values. Instead, the software advises comparing pre- and post-impact flow magnitudes using IHA parameter groups number 1 and 2, rather than EFC parameters. Therefore, the EFC is used only to examine and characterize the hydrological flow behavior during the baseline period and projected climate change scenarios.

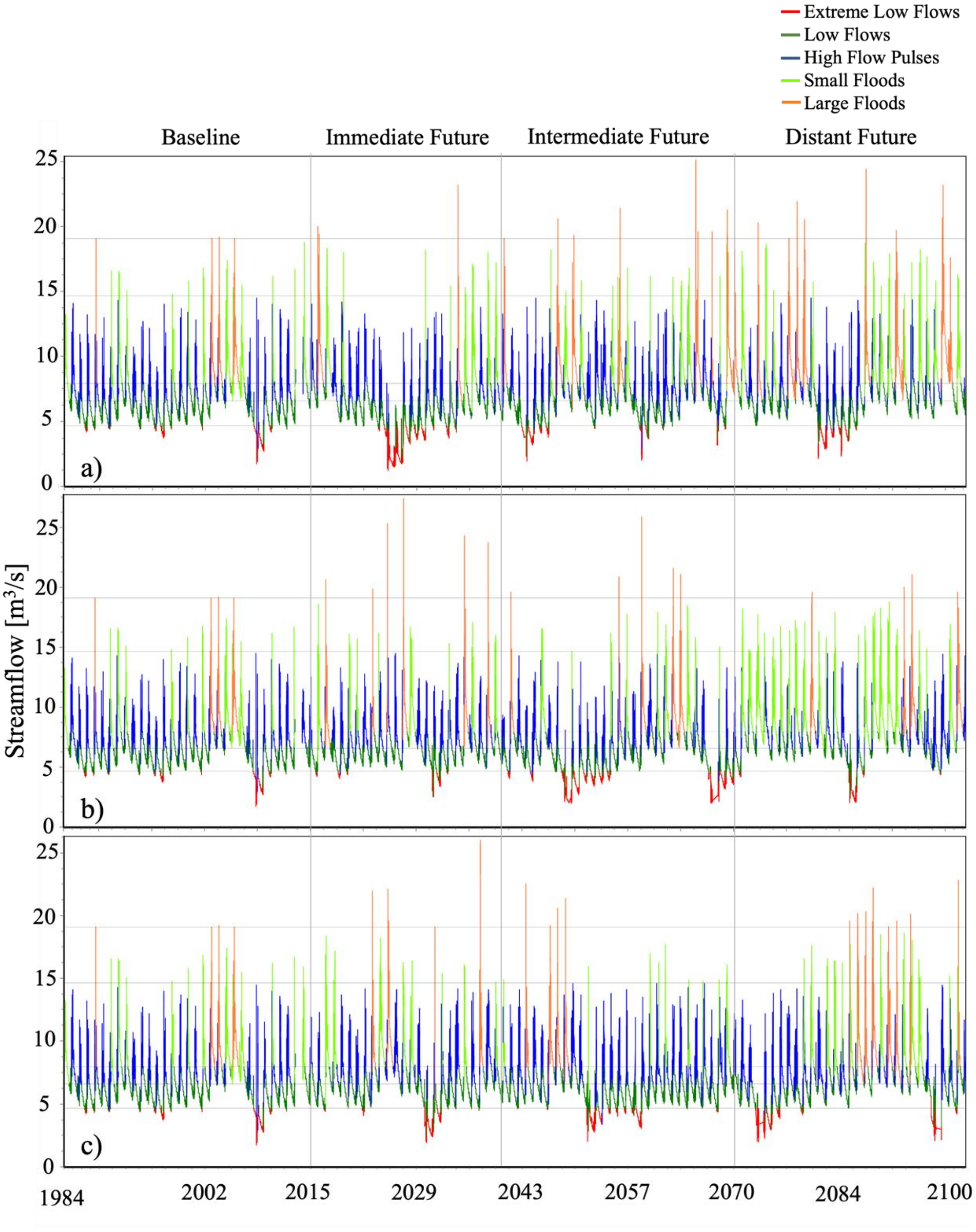
4. RESULTS AND DISCUSSION

When conducting two-period analyses, Indicators of Hydrological Alteration software (IHA) re-assigns each daily flow value to a different environmental flow component (EFC) category. As a result, the magnitude values of post-impact EFCs cannot be directly contrasted with the pre-impact values. Therefore, the historical and future periods are first characterized based on their EFCs on subsection 4.1. The following subsection (4.2) covers the pairwise comparison between the historical period and each scenario pathway (i.e., pre- and post-impact comparison), considering the Groups 1 and 2 of the IHA parameters and their respective range of variability.

4.1. Preparing the ground: characterization of the baseline and climate change scenarios

The historical period is characterized by high variability starting from 2003 (Figure 4), with three periods of large floods followed by four of extreme low flows. Before 2003, one large flood event was captured while no small or large floods were observed between 1992 and 1998. Extreme low flows were not particularly pronounced until 2008, where the most critical flow in the Guariroba River basin was identified in the historical simulations possibly due to a period of low rainfall amounts. The Guariroba River Basin presents annual patterns characteristic of the wet season, with high flow pulses during the summer followed by small and/or large floods right next to high flow pulses events. Jardine et al. (2015) showed that systems experiencing well-defined flood and drought patterns exhibit significant species richness and high rates of riparian forest production. Considering the remarkable richness of species in Brazil (SEGALLA et al., 2021; BRAZIL FLORA G, 2015; FORZZA et al., 2012; SOLBRIG, 1996), it is necessary to conduct studies assessing changes in hydrological patterns and their ecological connections.

Figure 4. Pre-impact (1980-2013) and Post-impact (2015-2100) Environmental Flow Components (EFC). This figure shows the periods of analysis Baseline (1980-2013), Immediate Future (2015-2040), Intermediate Future (2041-2070) and Distant Future (2071-2100) for SSP2-4.5 (a), SSP3-7.0 (b) and SSP5-8.5 (c). The horizontal lines represent the thresholds defined in the IHA software as mentioned in section 3.2.2.



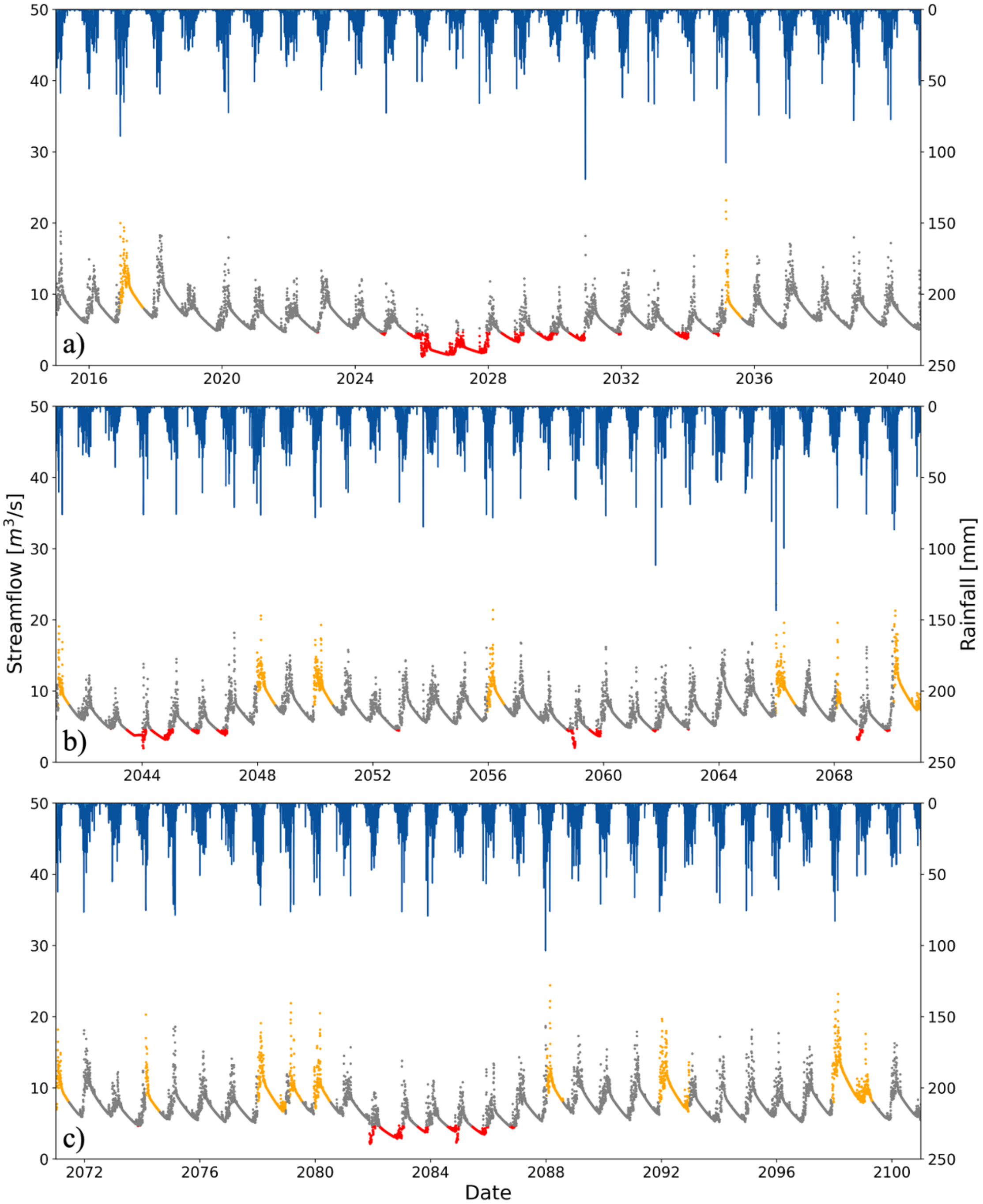
Source: Author

In the SSP2-4.5, several flood occurrences were observed, concentrated on the intermediate and distant future periods (Figure 4a), attributed to the high frequency and intensity of precipitation events (BALLARIN et al., 2024). Conversely, in the SSP3-7.0 scenario, these flood events are more concentrated in the immediate future, with rare occurrences projected in the distant future (Figure 4b). Similarly, there is an extensive period with no large floods in the SSP5-8.5 scenario between intermediate and distant future (2049 to 2086) (Figure 4c).

There is a small change in the flow pattern approaching the end of the century in the regional rivalry scenario (SSP3-7.0), with an increase in the low flow values (see Figure 4b) where the distant future presented mean low flow of 6.43 m^3/s while the immediate and intermediate presented 6.10 m^3/s and 6.19 m^3/s, respectively. 19 occurrences of small floods were found in the distant future period, which is a substantial increase compared to the 9 occurrences in each of the other two periods.

High flows and their variations, large and small floods, largely vary in the scenarios when analyzing the three future periods separately (immediate, intermediate, and distant). Shifts in high flow patterns may yield adverse effects on the morphological integrity of the river channel and disrupt the effort to rehabilitate water quality conditions following an extended period of low flows (The Nature Conservancy, 2009). Additionally, Poff and Zimmerman (2010) demonstrated that studies experiencing shifts in high flows often report disturbance in the life cycle and in the ecological communities, decreased species diversity, and the loss of sensitive species. Concurrently, in terms of climate change, high flow duration indicates a trend toward shorter but more intense precipitation events (flash floods).

Figure 5. Rainfall and Streamflow on SSP2-4.5 scenario by Swat+ model. Figure shows (a) Immediate Future (2015-1040), (b) Intermediate Future (2041-2070) and (c) Distant Future (2071-2100) and highlights the EFCs Extreme Low Flow (red color) and Large Floods (orange color) for the three periods.



Analysis of precipitation patterns alongside large flood events indicated that in SSP2-4.5, higher frequencies and intensities of rainfall events were observed in the intermediate and distant future. This contributed to an increased incidence of large floods during both periods (7 occurrences for each), in contrast to the 2 occurrences in the immediate future (see Figure 5). The intermediate and distant future presented events lasting up to 17 months; however, in general, the distant future displayed longer large floods.

In the SSP2-4.5 scenario (Figure 5), extreme low flows occurred 10, 12, and 6 times in the immediate, intermediate, and distant futures, respectively. The longest and most intense period of extreme low flow was estimated in the immediate future, between 2025 and 2031. Furthermore, in the intermediate future, greater intensity of extreme low flows was observed from 2043 to 2046. Additionally, in the distant future, these events spanned exclusively from 2081 to 2086.

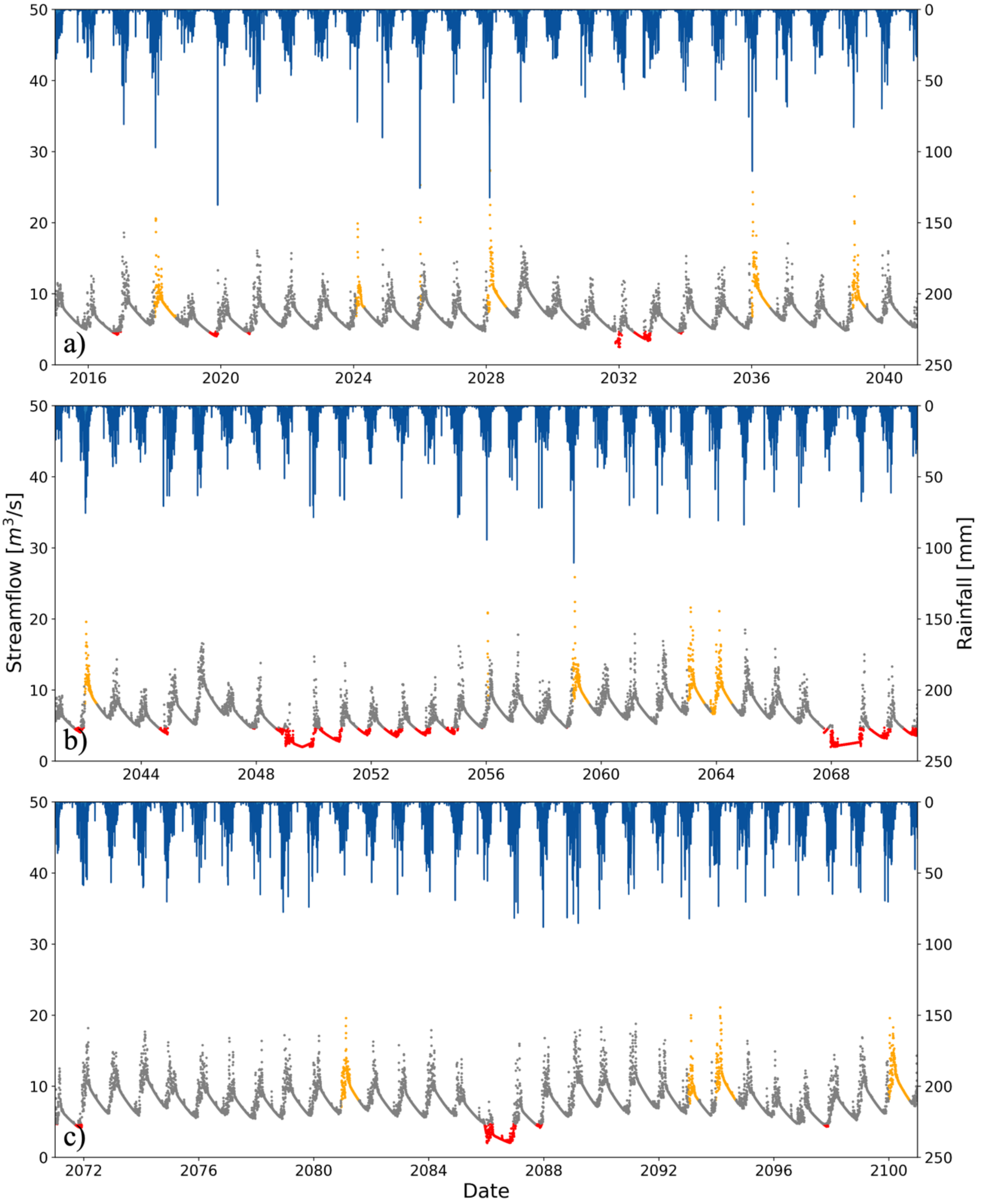
The results revealed a shift in streamflow patterns attributed to rainfall variability, in line with findings by Milly, Dunne, and Vecchia (2005). These patterns range from low flow to high flow pulses, along with small and large floods during the wet season, with a consistent return to extremely low flow during months characterized by low precipitation. In the SSP2-4.5 extreme low flow events typically begin in an average of 141.8 days after the end of rainfall in a period of high flow or small flood. The day count is backwards, starting from the extreme low flow event until the last day with precipitation greater than 1 mm in a high flow pulse or small flood event. On average, the months from February to April were marked by the end of the day count.

The SSP2-4.5 scenario for the immediate future suggests that recovering the river flow rate could be challenging, as it experienced the lowest frequency of extreme rainfall events, as highlighted by Ballarin et al. (2024), and the recovery from extreme low flows is directly linked to high rainfall amounts. It is important to note that only two large flood events occurred and there were no incidences of extreme low flow events during this time (See Figure 5). The intermediate future exhibits greater variation in precipitation intensities, leading to significant occurrences of extreme low flows and large floods, highlighting the system's instability and dependence on rainfall events. The distant future presented high precipitation amounts, long periods of large floods and few occurrences of extreme low flows.

SSP3-7.0 exhibited a higher concentration of events in the immediate future, specifically 6 large floods (refer to Figure 6). However, there is a subsequent increase in mean precipitation in the distant future, leading to a greater occurrence of small floods rather than large floods, as shown in Figure 4b. This may be attributed to the distribution of rainfall in the distant future, characterized by smaller peaks but more frequent rainfall events compared to the other two periods. Consequently, this results in a similar streamflow behavior, classified as small floods according to Figure 4b and Table 2 due to the two years of return interval event.

In the SSP3-7.0, a pattern is noted in the long extreme low flow events, which occurs approximately every 11 years in the basin, and they tend to last longer after 2045 (Intermediate future). The scenario showed the highest concentration of extreme low flow events in the intermediate future. It was observed 14 extreme low flow events, and the most pronounced concentration of events occurs between 2048 and 2055. In the period of simulation, the extreme low flow events usually begin an average of 150 days after the end of rainfall in a period of high flow or small flood. The immediate and distant futures presented 6 and 4 extreme low flow events, respectively, where the first is characterized as a drier period with lower average rainfall and significant precipitation peaks, reaching 137.62 mm in a single day, whereas the distant future exhibited distributed rainfall and a higher annual average precipitation.

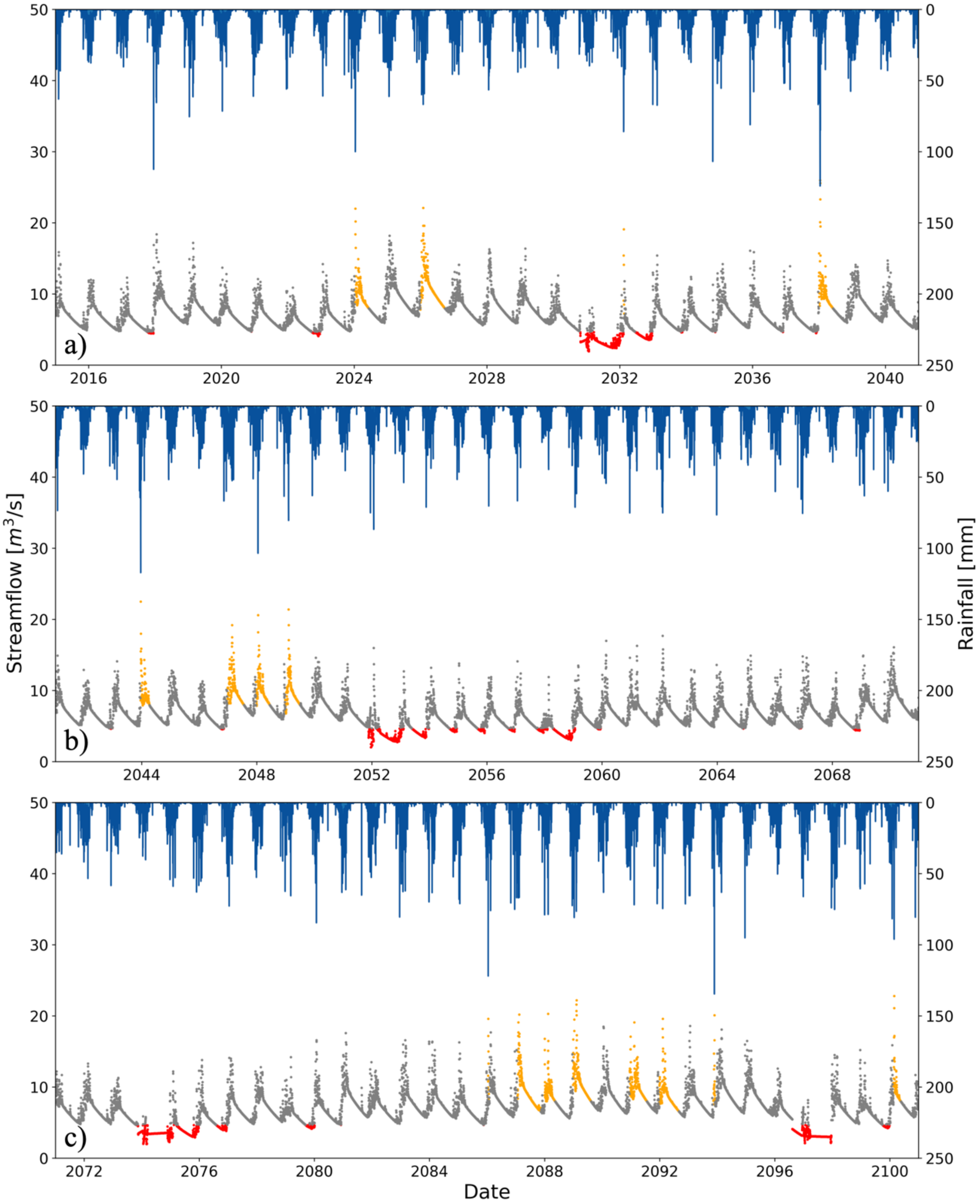
Figure 6. Rainfall and Streamflow on SSP3-7.0 scenario by Swat+ model. Figure shows (a) Immediate Future (2015-1040), (b) Intermediate Future (2041-2070) and (c) Distant Future (2071-2100) and highlights the EFCs Extreme Low Flow (red color) and Large Floods (orange color) for the three periods.



The fossil-fueled development scenario (SSP5-8.5) exhibited an increase in flood events in the distant future, with 8 large flood events, while the other two periods presented 4 events each. This increase was driven by high rainfall frequencies and intensities by the end of the century (SONE et al., 2022; LEE et al., 2021), and consequently higher mean precipitation amounts. Figure 7 shows that high-intensity precipitation is common from 2086 to 2093, coinciding with the occurrence of all large floods in the period. The intermediate future was marked by 4 events occurring between the years 2043 and 2049, mainly caused by large precipitation peaks and with an average large flood event duration of 6 months. In the immediate future, large flood events are spread out over the years and exhibited longer durations in 2024 and 2025, where precipitation presented better distribution throughout the months.

The most pessimistic scenario (SSP5-8.5) is defined by a sequence of extreme low flow events every 22 years. 8 occurrences were observed in both the immediate and distant future and 14 occurrences in the intermediate future. The intermediate future presented the highest number of extreme low flow events from 2051 to 2059, where lower precipitation levels were also observed (see Figure 6b). This is especially prominent post-2045, corroborating the extended phase with no large floods between 2049 and 2086 as mentioned earlier. In this scenario, extreme low flow events began on average 136 days after the end of rainfall in a period of high flow or small flood. This suggests high vulnerability, as it shows that this scenario is the most likely to experience extreme low flow in low precipitation conditions. Consecutive extreme low flow events in rivers may harm species. In the Guariroba basin SSP5-8.5 simulation, species are adapted to water availability, but the concentration of low flows (2051-2059) in the intermediate future could hinder species recovery. Studies by McDowall (1995) and Rolls, Leigh and Sheldon (2012) showed that such events can disrupt aquatic life recruitment and migration and introduce species unsuited for survival in low water.

Figure 7. Rainfall and Streamflow on SSP5-8.5 scenario by Swat+ model. Figure shows (a) Immediate Future (2015-1040), (b) Intermediate Future (2041-2070) and (c) Distant Future (2071-2100) and highlights the EFCs Extreme Low Flow (red color) and Large Floods (orange color) for the three periods.



There is an increasing trend in the duration of extreme low flow across scenarios, indicating the dry season may become longer in the future, which corroborate with previous studies (e.g., Gesualdo et al. (2019), Sone et al. (2022)). Extreme low flows represent challenges for ecological integrity and human needs, warning for changes in adequate habitat for organisms, in water temperatures and dissolved oxygen availability and in fresh water supply for both terrestrial wildlife animals and population. Despite the good uses of climate scenarios, ecological data and Environmental Flow Components (EFC) such as aiding in defining environmental flow targets and managing good practices in the basin, applying these standards to establish feasible management thresholds may be a challenge for water resources managers (ZHANG et al., 2015). There are two considerable limitations involved in this kind of study. Primarily, it is essential to acknowledge that climate change scenarios do not provide definitive future predictions; thus, caution is fundamental, and the utilization of climate change scenarios is limited to the analysis of order and magnitudes of change according to the historical simulations. This kind of analysis is an important step to improve water resources management plans and policies to consider the climate extremes uncertainties and risk. Furthermore, the EFC analysis purpose is to establish connections between observed ecological and hydrological data. However, the proper drawing of this relationship and feedback loops, as proposed by the ELOHA framework, was not possible due to the lack of ecological studies in the Guariroba River basin. This limitation was further mentioned by other studies such as those by Poff and Zimmerman (2010) and Poff and Matthews (2013). Although this limitation exists, efforts were made to overcome it by providing insights about the ecological implications of our findings.

4.2. Implications for water resources under climate uncertainty

Table 3 presents statistical metrics for both the pre-impact and post-impact periods. The SSP2-4.5 and SSP3-7.0 exhibited substantial similarities in mean annual flow, annual coefficient of variation (C.V.), flow predictability and constancy/predictability. On the other hand, these metrics for SSP5-8.5 were most closely aligned to the pre-impact period. Notably, SSP2-4.5 demonstrated an absence of flood-free days, which represents the longest continuous duration in days across all water years wherein flows remain at or below the high pulse threshold. River flow predictability ranges from 0 to 1, and the Guariroba river basin exhibits a high level of predictability characterized by well-defined seasons and patterns, as previously outlined. Mean annual flows exhibited a rise from the baseline period to the most pessimistic scenario. Subsequently, scenarios SSP2-4.5 and SSP3-7.0 displayed the greatest mean annual flows due to intense occurrences of high flow pulses, small floods, and large floods.

Small floods and large floods enable organisms and fish to move to other areas with warmer temperatures, more nutrients and substantial food resources, maintain balance of species, disburse seed and fruits of riparian plants and trigger new phases in life cycle. However, these periods are particularly noteworthy, especially during extreme conditions. Studies such as Piniewski et al. (2017), Silva-Santos et al. (2004), and Meffe and Minckley (1987) identified a loss of species richness following extreme flood events due to their substantial impact on the biological and physical composition of the river and its floodplain.

Table 3. Non-parametric scoreboard with statistics parameters that apply to the period of analysis (pre-impact and post-impact periods) as a whole.

Statistical metrics	**Pre-impact period: 1984-2013**	**Post-impact period: 2015-2100**		
	Baseline	SSP2-4.5	SSP3-7.0	SSP5-8.5
Mean annual flow	6.93	7.22	7.22	7.01
Annual C. V.	0.3	0.34	0.33	0.32
Flow predictability	0.78	0.71	0.71	0.73
Constancy/predictability	0.87	0.9	0.9	0.88
% of floods in 60d period	0.51	0.48	0.52	0.47
Flood-free season	27	0	8	25

Our discussion from now is focused on the parameters that describe extreme flow regimes (i.e., parameters from group 1 and group 2). The results were placed into three categories of hydrological alterations (HA): low, middle, and high boundaries. A positive HA factor indicates an increase in the frequency of records within a category from the pre- to post-impact period while a negative value signifies a decrease in frequency. The degree of alteration can be classified as follows: small or no alteration when HA ranges from 0.0 to 0.33, moderate alteration when HA ranges from 0.34 to 0.67, and high alteration when HA ranges from 0.68 to 1.0 (RICHTER et al., 1998).

The analysis of median monthly flow alterations (group 1) reveals a consistent increase across all post-impact scenarios for every month, except January, corroborating the scores in Table 3 previously discussed. Figure 8 shows median monthly flows and their respective Range of Variability Approach (RVA) with the high, middle, and low boundaries. Detailed results of RVA boundaries delineating hydrologic alterations are presented in the Appendix. Among these scenarios, SSP2-4.5 exhibited the most pronounced hydrologic alterations in median monthly flows, with a notable decrease in middle and low boundary frequency. This indicates that the more frequent flow records are now in the high boundary in the climate scenario.

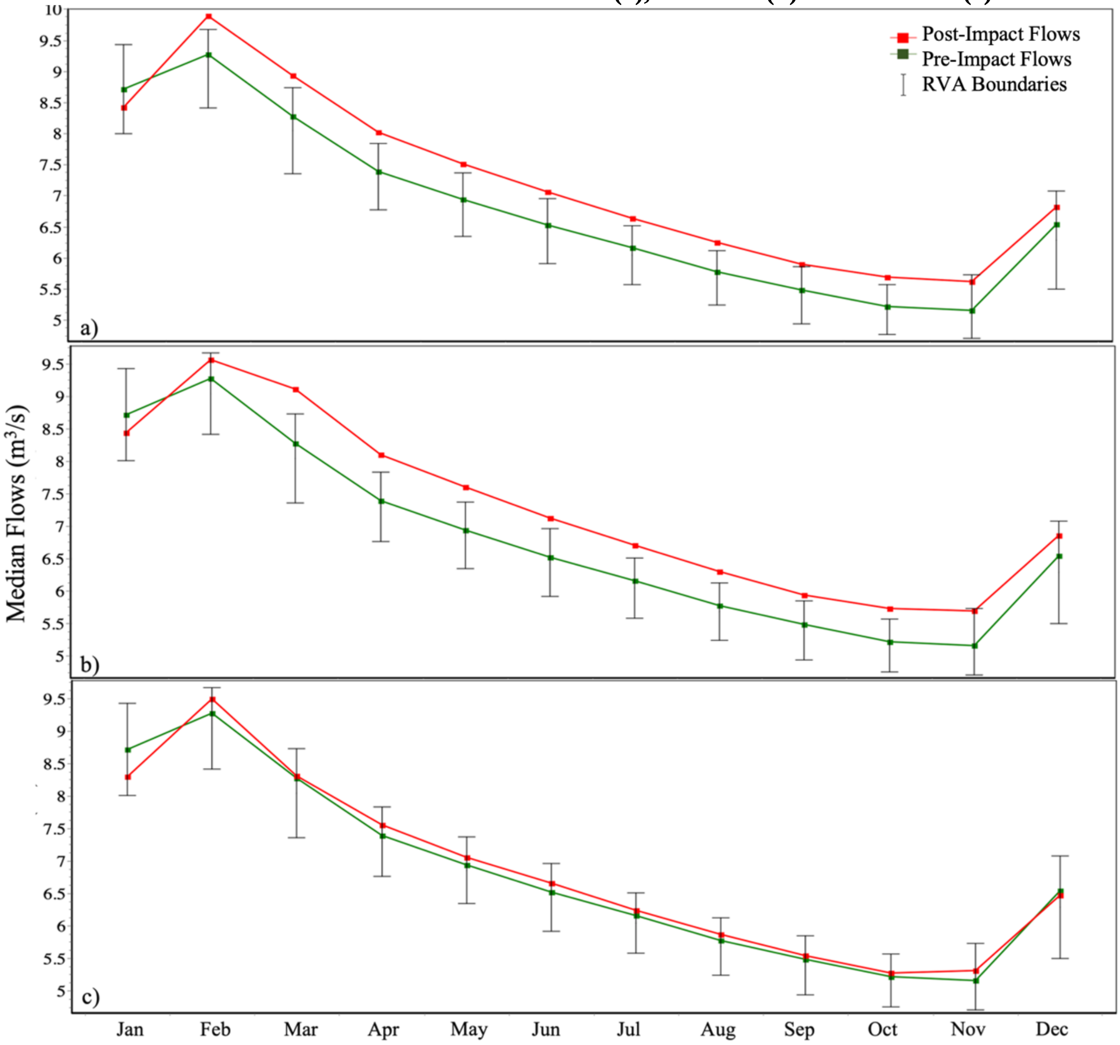
For Group 1 parameters, February stands out as the month with the most significant hydrologic alteration in the SSP2-4.5 scenario according to the middle RVA boundary. Nevertheless, February hydrologic alteration is classified as moderate according to Richter et al. (1998), with an HA factor of -0.58. April and May emerged with the most pronounced alterations at the high boundary, denoted by a 0.71 HA factor. In other words, negative HA as in the middle boundary in the SSP2-4.5 suggests that occurrences in this category of flow regime are less frequent in this scenario than expected based on the observed frequency in the historical period. Conversely, the SSP5-8.5

displayed the highest hydrologic alteration occurring in the RVA low boundary (-0.51 in June and September), yet it was still considered moderate, and the lowest hydrologic alteration in the middle boundary (-0.02 in December).

It is noteworthy that median monthly flows are higher within the context of climate change scenarios. The question then arises: Despite the climate change scenarios, can higher median monthly flows be considered a positive outcome for ecological needs and water supply? Water supply and ecological maintenance demands consistent water flow patterns, which may not be the Guariroba river basin case on climate change scenarios. Instead, an increase in median monthly flows was observed due to intense precipitation events, leading to more frequent occurrences of extreme flow events, such as small and large floods. Then, corroborating with the low frequency of flows in the middle RVA boundary and the high frequency on high RVA boundary.

When considering exclusively median monthly outcomes during the periods before and after the impact, one might be inclined to perceive positive flow outcomes within climate change scenarios, as they indicate greater water availability in the basin. However, a comprehensive assessment demands balance, revealing that the observed elevation in median flows is due to the EFC trends discussed in section 4.1, such as increases in extreme high flow events (small and large floods) concomitant with reductions in low flow events but increase in intensity (extreme low flows). Moreover, the RVA analysis demonstrates increased occurrence of high boundary frequencies and concurrent reductions in middle and lower boundary frequencies for SSP2-4.5 and SSP3-7.0. It indicates intensified high flow events and increased fluctuations, with a reduction of middle and lower boundaries flow regimes.

Figure 8. Median monthly flows for pre-impact and post-impact periods and their respective RVA boundaries for the three scenarios SSP2-4.5 (a), SSP3-7.0 (b) and SSP5-8.5 (c).



The median monthly flows play a role in shaping factors such as water temperature, oxygen concentrations, photosynthesis rates, habitat accessibility for aquatic organisms, soil moisture availability for plants, water accessibility for terrestrial animals, and the accessibility of nesting sites for predators. Additionally, drastic alterations due to extreme events are unlikely to lead to improvements in agriculture or water supply. More intense floods and droughts can decrease water infiltration into the soil and deteriorate soil erosion rates. Especially for water supply purposes, it is key to promote the recharge of shallow and deep aquifers, as they are important to maintaining the baseflow during the dry period.

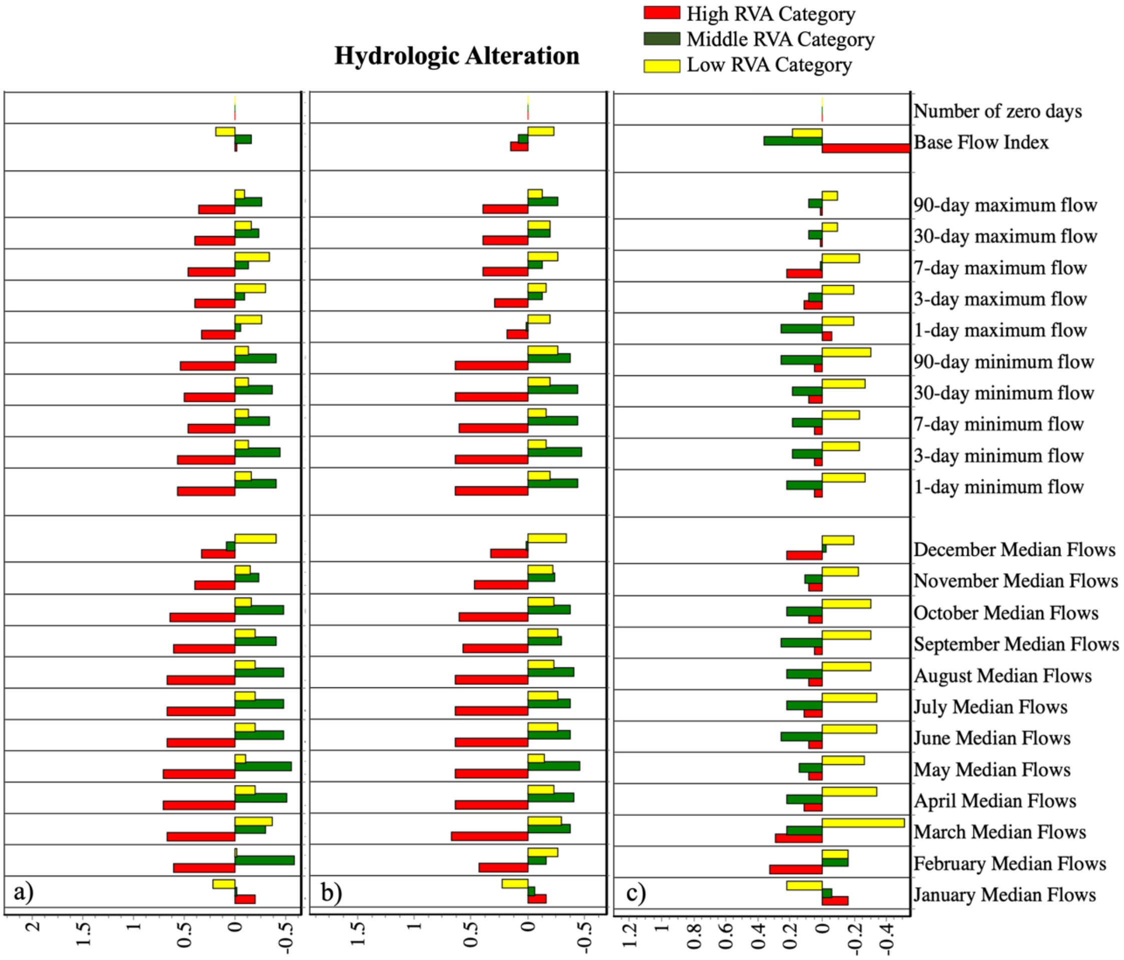
Regarding the second group of parameters (extreme conditions) in Table 4, the zero-flow days were not identified; the baseflow index also exhibited minimal fluctuation when comparing median values of the pre- and post-impact periods. It’s important to note that in the RVA analysis, baseflow index showed minimal alteration for SSP2-4.5 and SSP3-7.0, while in the most pessimistic scenario it was the parameter that displayed the higher alteration with decrease in high boundary frequency and increases in low and middle boundaries, and consequently it results in the smallest median baseflow when compared to the other scenarios and baseline period. Across all scenarios, the moving averages for both minimum and maximum flows showed an increase from the pre- to post-impact period. However, enhancing moving averages might present challenges since parameters are based on median values, and climate change scenarios reveal substantial fluctuations in extremes. This suggests periods featuring intense droughts and extensive floods, leading to a notable disturbance in future flow averages. Modifications on river patterns may be a barrier to the planning and management of the basin, given the significant variability in flow, requiring continuous revisions of water management plans and regulations. Moreover, it has the potential to yield adverse impacts on ecosystem processes, sediment transport, and water quality. Parolin (2012) asserts that extreme water conditions are intricately tied to floodplain inundation and the formation of plant communities adapted to predicted floods while these events have been also associated with sediment erosion and deposition, which could shape extensive river habitats (CONSTANTINE et al., 2014).

Table 4. Group 2 parameters for extreme events in the pre-impact period and post-impact periods for the three future scenarios SSP2-4.5, SSP3-7.0 and SSP5-8.5.

Group 2	Pre-impact	Post SSP2-4.5	Post SSP3-7.0	Post SSP5-8.5
1-day minimum	4.83	5.21	5.27	4.91
3-day minimum	4.85	5.25	5.32	4.98
7-day minimum	4.93	5.32	5.39	5.05
30-day minimum	5.13	5.47	5.55	5.20
90-day minimum	5.31	5.71	5.77	5.35
1-day maximum	14.65	16.10	15.80	14.90
3-day maximum	13.35	14.90	14.50	13.82
7-day maximum	11.52	13.07	12.91	12.54
30-day maximum	10.02	10.77	10.65	10.51
90-day maximum	9.01	9.58	9.65	9.10
Number of zero days	0	0	0	0
Base flow index	0.72	0.73	0.73	0.72

In Figure 9 (a), (b), and (c), the increase in the high RVA category is evident across nearly all parameters, particularly pronounced in scenarios SSP2-4.5 and SSP3-7.0. Conversely, a decline in the frequency of parameter values within the low category is observable in SSP5-8.5 (negative HA factor). This suggests that these parameters tend to be situated within the median or high categories. When focusing on the middle RVA category, it is worth noting that SSP2-4.5 and SSP3-7.0 display negative HA factors, emphasizing the significant changes in extreme flow regimes in these two scenarios also corroborated the EFC and IHA parameters.

Figure 9. IHA parameters used in this study and their hydrologic alteration to each RVA category (high, middle, and low) for SSP2-4.5 (a), SSP3-7.0 (b) and SSP5-8.5 (c).



Median monthly flows are affected by climate scenarios and show higher difference between the baseline and SSP2-4.5 and SSP3-7.0 scenarios, presenting an increase in the high RVA category and concurrently a decrease in the middle and low categories. Additionally, SSP5-8.5 and the baseline are alike even though the SSP5-8.5 exhibits the most accentuated decrease in low RVA boundary. In other words, median monthly flow frequencies are expected to present higher values. Results showed a disparity between the baseline and the SSP2-4.5 and SSP3-7.0 scenarios. This contrast entails a rise in the frequency of the higher-boundary category, with the parameters reaching high hydrological alteration (0.71 HA) for the SSP2-4.5 and approaching the moderate to high alteration range for SSP3-7.0 (0.67 HA). Reductions in frequencies were also noted for the middle (reaching -0.58 HA for the SSP2-4.5 and -0.46 for the SSP3-

7.0) and lower categories (reaching -0.37 HA for the SSP2-4.5 and -0.34 for the SSP3-7.0) (See Appendix Table 11, 12 and 13). Moreover, while the most pessimistic scenario and the baseline share some similarities, a significant decrease classified as moderate alteration in the lower boundary frequency (-0.51 HA) is evident. Additionally, an increase in the frequency of high values, representing median monthly flow frequencies, was expected. However, concerning Hydrologic alteration RVA, the high boundary category and middle boundary category present results indicating small or no alteration, with HA factors reaching 0.33 and 0.26, respectively. In January, despite displaying higher medians compared to the historical period (see Figure 8), it stands out for the decrease in frequencies of values in the middle and high categories, concentrating significantly in the low category. This trend contrasts with the other months analyzed. Thus, it is observed that the disparity highlighted in Figure 8 (for a more detailed analysis, see Table 9 in the Appendix) is minimal during the first month of the year, considered small or no change in HA for all considered scenarios.

SSP2-4.5 suggests that baseflow tends to decrease, as the frequencies of occurrences in the low category increased, while those in the middle and high categories decreased by 0.19 HA, -0.16 HA, and -0.02 HA, respectively. In SSP3-7.0, the high (0.15 HA) and middle (0.08 HA) category frequencies increased, while the low category decreased (-0.23 HA), indicating an overall increase in baseflow. Finally, the SSP5-8.5 scenario showed a significant decrease in the frequency of the high category (-0.55 HA). In comparison, the middle (0.36 HA) and low (0.19 HA) categories experienced an increase, suggesting that the frequency of baseflow values in this scenario tends to remain in the range of low and mainly medium values. The baseflow index exhibits varying trends across scenarios; however, similarly to McDaniel and O’Donnell (2019), it consistently maintains a baseflow value comparable to that of the historical period. This similarity may be attributed to the degree of alteration, classified as small or no change in scenarios SSP2-4.5 and SSP3-7.0, and as moderate alteration in the scenario most similar to the historical period (SSP5-8.5).

IHA software estimates the baseflow index by the 7-day minimum flow, which represents the flow that remains for most of the time in the river, and the annual mean flow ratio. Based on this ratio, Figure 9 (further details in Table 10 of the Appendix) showed that the 7-day minimum flow increased in the three scenarios SSP2-4.5, SSP3-7.0, and SSP5-8.5 (5.32, 5.39, and 5.05, respectively) compared to the historical data (4.93), suggesting that the annual mean precipitation also increased. Results from the baseflow index and 7-day minimum flow showed that the scenarios exhibited no significant increases in the annual mean flow, indicating results closer to the historical data. Evapotranspiration modeled data (Figures 10, 11, and 12 in the Appendix) follow precipitation patterns and do not suggest significant changes in the scenarios, such as increasing of evapotranspiration during dry periods. This implies that there is likely no influence of evapotranspiration during extreme low flow periods or in the decrease of the baseflow index, given that the basin evapotranspiration is already in a water-limited condition.

The moving averages derived from maximum and minimum flows also experienced notable influences due to climate changes, reflecting conditions associated with extreme events. Based on these moving averages, moderate changes are expected in the high RVA boundary, HA values reaching 0.57 for SSP2-4.5 and 0.64 for SSP3-7.0. Following the HA trends in the parameters from Group 1, there is a decrease in the frequency of low and middle boundaries of parameters from Group 2 considering both the SSP2-4.5 and SSP3-7.0. Moreover, SSP5-8.5 shows negative HA for the low RVA boundary, indicating a higher occurrence of values exceeding the middle and high boundaries.

Extreme events of floods and droughts are increasing worldwide (UNISDR and CRED, 2018; HIRABAYASHI et al, 2008). The future is characterized by significant uncertainty due to climate change, which in turn amplifies governance challenges through the intensification of extreme hydrological events (UNESCO, 2020). The challenge of managing unexpected events is concerning, especially considering the projected increase in extreme hydrological events due to climate change (IPCC, 2012). Both Group 1 and Group 2 describe extreme flow conditions and due to that they assume critical significance in the discussions about river management and ecological protection, establishing essential limits for governmental bodies and stakeholders in terms of water allocation and environmental targets. Outcomes stemming from RVA analysis, as increased hydrological modifications, have direct repercussions on the environment, from species loss to shifts in river morphology, alterations in temperature and water oxygen levels, and therefore significantly impacts on water provision.

4.3. Further research implications

The Guariroba River Basin may experience significant hydrological changes in the future, characterized by a pronounced escalation in extreme flow events such as floods and droughts. Thus, the basin may need more investments following the concept of conservationist agriculture, applying combined practices such as vertical mulching, terraces, no tillage system, and soil cover to increase infiltration rates and decrease sediment transportation to maintain the water quality in the river and the baseflow during the long dry seasons. Also, climate change influence on the basin demands management of agricultural deforestation and maintain vegetation on vulnerable areas around rivers to enable ecological natural restauration for organisms and plants due to extreme events. Recognizing the basin importance, our findings may aid in future decision making for Guariroba and other basins, considering not only water quantity but also ecological responses and their importance for the water supply, agriculture and for species balance.

The ELOHA framework application may bring improvements to water resources management in Brazil, overcoming the current criteria limitations such as $Q_{7,10}$, Q_{90}, or Q_{95}, adopted by governmental legislative bodies. These criteria do not consider the needs of all the components affected by water withdrawal such as aquatic biota, terrestrial species, water availability for plants, public water supply, and agriculture. The ELOHA framework addresses these gaps by incorporating water use, social impact, and, especially, ecological impact to define environmental flows. Despite current limitations such as the lack of ecological and hydrologic data, this study showed the method's positive potential by the framework adaptation to assess climate change scenarios, hydrological alteration estimative, extreme flow analysis and encourage future interdisciplinary research in hydrology, hydraulics, ecology, and social sciences. Investments in this research area may yield significant advantages when applying the ELOHA framework due to the hydrological, social and ecological aspects covered using the framework. While direct application in Brazil may not be feasible, at present, the proposed adaptation facilitates additional research and the implementation of ELOHA methodologies for the granting of water resource rights.

5. CONCLUSION

Historical flow data are used to define waterbody minimum flows based on the regional water uses, and important information such as river flow seasonality, animal and plant species needs, and climate change projections are often not considered when decision-making. This study presents the streamflow alterations and potential ecological responses in the Guariroba River Basin taking into account the ELOHA framework, historical observation data from 1984 to 2013 and climate change scenarios forced by three emission levels (SSP2-4.5, SSP3-7.0 and SSP5-8.5) from 2015 to 2100.

In terms of median values, the most pessimistic scenario (SSP5-8.5) exhibited a greater resemblance to the historical period, indicating moderate alteration. Conversely, the SSP2-4.5 and SSP3-7.0 showed similar results displaying high hydrological alteration, although they differed from the baseline period. Despite the similarities of SSP5-8.5 to the historical median results, it emerged as the scenario not only with the highest occurrence of extreme low flow events, but also with the highest concentration of large floods in the distant future, attributed to instances of high rainfall frequencies and intensities. Moreover, SSP5-8.5 presented higher vulnerability to experience extreme low flow events in cases of low precipitation conditions.

Shifts in the river flow, particularly caused by extreme events, may not be accepted by local species, due to potential alterations in water temperature, channel morphology, oxygen levels, and nutrient distribution. This could lead to mortality, predator increases, and the proliferation of invasive plant species. Furthermore, such shifts could disrupt the life cycles, diversity, and habitats of both aquatic and terrestrial organisms. In terms of water supply management, future alterations in streamflow frequencies and intensities of extreme events, such as floods and droughts, could lead to reduced water infiltration, increased erosion rates within the basin, and compromised water quality. These changes may require continuous revisions of water plans and regulations within the basin, as well as increased financial investment for the restoration of affected areas, water treatment, and distribution infrastructure. Considering the basin's water use for agriculture, supply, and the needs of local species, we suggested implementing combined practices in agriculture and vegetation management in vulnerable areas. These practices aim to reduce sediment transportation, increase infiltration, maintain streamflow water quality, and improve ecological restoration efforts in floods and droughts.

Challenges in using the ELOHA in Brazil include limited studies, hydrological and ecological data, as well as high costs and time for multidisciplinary research. For future steps, it is recommended land use and land cover changes and ecological data assessment, to contrast with flow and precipitation simulations for a better characterization of the basin. Nonetheless, our study, using the ELOHA adaptation, advances water management understanding and invites ecological researchers to address basin dynamics and future research needs on ecological-flow linkages.

REFERENCES

ABEBE, W. B. et al. **Environmental flow assessment and implications on sustainability of aquatic ecosystems in Ethiopia: A literature review on global and national evidencesEnvironmental Development**Elsevier B.V., , 1 dez. 2022.

ACREMAN, M. C.; FERGUSON, A. J. D. Environmental flows and the European Water Framework Directive. **Freshwater Biology**, v. 55, n. 1, p. 32–48, jan. 2010.

ANACHE, J. A. A. et al. Assessment of methods for predicting soil erodibility in soil loss modeling. **Geociencias**, v. 34, n. 1, p. 32–40, 2015. ISSN 1980900X.

ARIAS, M. E. et al. Impacts of climate change and deforestation on hydropower planning in the Brazilian Amazon. **Nature Sustainability**, v. 3, n. 6, p. 430–436, 1 jun. 2020.

ARTHINGTON, A. H. et al. Environmental flow requirements of fish in Lesotho Rivers using the drift methodology. **River Research and Applications**, v. 19, n. 5–6, p. 641–666, set. 2003.

ARTHINGTON, A. H. et al. **The Challenge of Providing Environmental Flow Rules to Sustain River EcosystemsSource: Ecological Applications**. [s.l: s.n.].

BALLARIN, A. S. et al. Frequency rather than intensity drives projected changes of rainfall events in Brazil. **Earth's Future**, 12, e2023EF004053, 2024. Disponivel em: <https://doi.org/10. 1029/2023EF004053>.

BELMAR, O.; VELASCO, J.; MARTINEZ-CAPEL, F. Hydrological classification of natural flow regimes to support environmental flow assessments in intensively regulated Mediterranean rivers, Segura River Basin (Spain). **Environmental Management**, v. 47, n. 5, p. 992–1004, 2011.

BENTSEN M, et al. (2019) NCC NorESM2-MM model output prepared for CMIP6 CMIP 1pctCO2.

BIEGER, K. et al. Introduction to SWAT+, A Completely Restructured Version of the Soil and Water Assessment Tool. **Journal of the American Water Resources Association**, v. 53, n. 1, p. 115–130, 2017.

BRAZIL FLORA G. Brazilian Flora 2020 project - Projeto Flora do Brasil 2020. Version 393.398. **Instituto de Pesquisas Jardim Botanico do Rio de Janeiro**. Checklist dataset https://doi.org/10.15468/1mtkaw accessed via GBIF.org on 2023-12-24.

BUCHANAN, C. et al. A test of The Ecological Limits of Hydrologic Alteration (ELOHA) method for determining environmental flows in the Potomac River basin, U.S.A. **Freshwater Biology**, v. 58, n. 12, p. 2632–2647, dez. 2013.

CANNON, A. J.; SOBIE, S. R.; MURDOCK, T. Q. Bias correction of GCM precipitation by quantile mapping: How well do methods preserve changes in quantiles and extremes? **Journal of Climate**, v. 28, n. 17, p. 6938–6959, 2015.

CAPÍTULO, L. R. et al. Bases para estudiar las alteraciones del régimen hidrológico y su importancia ecológica en la Argentina. **Ecología Austral**, v. 32, p. 273–296, 2022.

CHAGAS, V. B. P.; CHAFFE, P. L. B.; BLÖSCHL, G. Climate and land management accelerate the Brazilian water cycle. **Nature Communications**, v. 13, n. 1, 1 dez. 2022.

CONSTANTINE, J. A. et al. Sediment supply as a driver of river meandering and floodplain evolution in the Amazon Basin. **Nature Geoscience**, v. 7, n. 12, p. 899–903, 11 dez. 2014.

CUÉLLAR, F. G.; NEIRA, N. O. The Potential Of Kohonen Method For Classifying Rivers Focused The Potential Of Kohonen Method For Classifying Rivers Focused On Regional Environmental Flow Determination With ELOHA On Regional Environmental Flow Determination With ELOHA. In: **International Conference on Hydroinformatics**, 2014, New York City, USA.

DEARING, J. A. et al. Safe and just operating spaces for regional social-ecological systems. **Global Environmental Change**, v. 28, n. 1, p. 227–238, 2014.

DIAS, L. C. P. et al. Effects of land cover change on evapotranspiration and streamflow of small catchments in the Upper Xingu River Basin, Central Brazil. **Journal of Hydrology: Regional Studies**, v. 4, n. PB, p. 108–122, 1 set. 2015.

DOS SANTOS, D. J. et al. Future rainfall and temperature changes in Brazil under global warming levels of 1.5°C, 2°C and 4°C. **Sustentabilidade em Debate**, v. 11, n. 3, p. 57–73, 31 dez. 2020.

(EC-Earth) E-EC (2019) EC-Earth-Consortium EC-Earth3 model output prepared for CMIP6 ScenarioMIP ssp370.

FELIPE-LUCIA, M. R.; COMÍN, F. A.; ESCALERA-REYES, J. A framework for the social valuation of ecosystem services. **Ambio**, v. 44, n. 4, p. 308–318, 21 out. 2014.

FORZZA, R. C., et al. New Brazilian Floristic List Highlights Conservation Challenges. **BioScience**, vol. 62, no. 1, 2012, pp. 39–45, 2012.

GASSMAN, P. W.; SADEGHI, A. M.; SRINIVASAN, R. Applications of the SWAT Model Special Section: Overview and Insights. **Journal of Environmental Quality**, v. 43, n. 1, p. 1–8, jan. 2014.

GESUALDO, G. C. et al. Assessing water security in the São Paulo metropolitan region under projected climate change. **Hydrol. Earth Syst. Sci.**, 23, p. 4955–4968, 2019. Disponível em: < https://doi.org/10.5194/hess-23-4955-2019>.

GESUALDO, G. C. et al. Unveiling water security in Brazil: current challenges and future perspectives. **Hydrological Sciences Journal**, v. 66, n. 5, p. 759–768, 2021.

GIBSON, C. A. et al. Flow regime alterations under changing climate in two river basins: Implications for freshwater ecosystems. **River Research and Applications**, v. 21, n. 8, p. 849–864, out. 2005.

GIDDEN, M. J. et al. Global emissions pathways under different socioeconomic scenarios for use in CMIP6: A dataset of harmonized emissions trajectories through the end of the century. **Geoscientific Model Development**, v. 12, n. 4, p. 1443–1475, 12 abr. 2019.

GITHUI, F. et al. Climate change impact on SWAT simulated streamflow in western Kenya. **International Journal of Climatology**, v. 29, n. 12, p. 1823–1834, out. 2009.

GRANDE, P. M. C.; Águas Guariroba S/A. **Plano de manejo da Área de Proteção Ambiental dos mananciais do córrego Guariroba - APA do Guariroba**. Campo Grande, 2008. I.

GUDMUNDSSON, L. et al. Globally observed trends in mean and extreme river flow attributed to climate change. 2021.

HEGERL, G. C. et al. Detectability of Anthropogenic Changes in Annual Temperature and Precipitation Extremes. **American Meteorological Society**, 17, p 3683-3700, 2004.

HIRABAYASHI, Y. et al. Global projections of changing risks of floods and droughts in a changing climate, **Hydrological Sciences Journal**, 53:4, 754-772, 2008. DOI: 10.1623/hysj.53.4.754

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. Future Global Climate: Scenario-based Projections and Near-term Information. In: **Climate Change 2021 – The Physical Science Basis**. [s.l.] Cambridge University Press, 2023. p. 553–672.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (eds Field, C.B. et al.) Cambridge Univ. Press, 2012.

JARDINE, T. D. et al. Does flood rhythm drive ecosystem responses in tropical riverscapes? **Ecology**, 96(3), pp. 684–692, 2015.

JHA, M. K. Evaluating hydrologic response of an agricultural watershed for watershed analysis. **Water (Switzerland)**, v. 3, n. 2, p. 604–617, 2011.

KARR, J. R. Biological integrity: a long-neglected aspect of water resource management. **Ecological Applications**, v. 1, n. 1, p. 66–84, 1991.

KING, J.; BROWN, C. **Environmental Flows: Striking the Balance between Development and Resource Protection**. [s.l: s.n.].

KURIQI, A. et al. Flow regime aspects in determining environmental flows and maximising energy production at run-of-river hydropower plants. **Applied Energy**, v. 256, 15 dez. 2019.

LEE, J. Y. et al. Future global climate: Scenario-based projections and near-term information. In: Masson-Delmotte V, Zhai P, Pirani A et al (eds) Climate Change 2021: The Physi- cal Science Basis. **Contribution of Working Group I to the Sixth Assessment Report of the Inter- governmental Panel on Climate Change**. Cambridge University Press, p 195, 2021.

LEROY POFF, N. et al. **The Natural Flow Regime**. [s.l: s.n.].

LOVATO T, PEANO D, BUTENSCHÖN M (2021) CMCC CMCC-ESM2 model output prepared for CMIP6 ScenarioMIP ssp245.

MAASS, J. M. et al. **Ecosystem Services of Tropical Dry Forests: Insights from Long-term Ecological and Social Research on the Pacific Coast of Mexico**. [s.l.] and Society, 2005. Disponível em: <http://www.ecologyandsociety.org/vol10/iss1/art17/>.

MACKAY, S. J.; ARTHINGTON, A. H.; JAMES, C. S. Classification and comparison of natural and altered flow regimes to support an Australian trial of the Ecological Limits of Hydrologic Alteration framework. **Ecohydrology**, v. 7, n. 6, p. 1485–1507, 1 dez. 2014.

MAGRIN, G. O. et al. 2014: Central and South America. In: Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. Maccracken, P.R. Mastrandea, And L. . W. (Ed.). . **Climate Change 2014: Impacts, Adaptation, and**

Vulnerability. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2014. p. 1499–1566.

MAPBIOMAS (2019) Project MapBiomas - Collection version 4.1 of Brazilian Land Cover & Use Map Series. https://plataforma.mapbiomas.org/map#coverage. Accessed 15 Mar 2020

MARTIN, D. M.; LABADIE, J. W.; POFF, N. L. Incorporating social preferences into the ecological limits of hydrologic alteration (ELOHA): A case study in the Yampa-White River basin, Colorado. **Freshwater Biology**, v. 60, n. 9, p. 1890–1900, 1 set. 2015.

MCDANIEL, R. D.; O’DONNELL, F. C. Assessment of Hydrologic Alteration Metrics for Detecting Urbanization Impacts. **Water**, 11, 1017, 2019. doi:10.3390/w11051017

MCDOWALL, R. M. Seasonal pulses in migrations of New Zealand diadromous fish and the potential impacts of river mouth closure. **New Zealand Journal of Marine and Freshwater Research**. V (29), p 517–526, 1995.

MEFFE GK; MINCKLEY WL. Persistence and Stability of Fish and Invertebrate Assemblages in a Repeatedly Disturbed Sonoran Desert Stream. **The American Midland Naturalist**. 117: pp. 177–191, 1987.

MILLY, P. C. D.; DUNNE, K. A.; VECCHIA, A. V. Global pattern of trends in streamflow and water availability in a changing climate. **Nature**. 438(7066), p 347–350, 2005. doi:10.1038/nature04312

MILLY, P. C. D. et al. Climate change: Stationarity is dead: Whither water management? **Science**, 1 fev. 2008.

MULLAN, D.; FAVIS-MORTLOCK, D.; FEALY, R. Addressing key limitations associated with modelling soil erosion under the impacts of future climate change. **Agricultural and Forest Meteorology**, v. 156, p. 18–30, 15 abr. 2012.

NÉMETHY, S. A. et al. Environmental Viability Analysis of Connected European Inland–Marine Waterways and Their Services in View of Climate Change Atmosphere. **MDPI**, 1 jun. 2022.

NETO, A. C. et al. Impact of climate change on groundwater recharge in a Brazilian Savannah watershed. **Theoretical and Applied Climatology**, v. 143, p. 1425–1436, 2021.

NÓBREGA, R. L. B. et al. Effects of conversion of native cerrado vegetation to pasture on soil hydro-physical properties, evapotranspiration and streamflow on the Amazonian agricultural frontier. **PLoS ONE**, v. 12, n. 6, 1 jun. 2017.

O’BRIEN, G. C. et al. A regional-scale ecological risk framework for environmental flow evaluations. **Hydrology and Earth System Sciences**, v. 22, n. 2, p. 957–975, 2018.

O’NEILL, B. C. et al. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. **Geoscientific Model Development**, v. 9, n. 9, p. 3461–3482, 28 set. 2016.

O’NEILL, B. C. et al. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. **Global Environmental Change**, v. 42, p. 169–180, 1 jan. 2017.

PAROLIN, P. Diversity of adaptations to flooding in trees of amazonian floodplains. **Botânica**, No 63, p 7-28 São Leopoldo: Instituto Anchietano de Pesquisas, 2012.

PÉREZ-SÁNCHEZ, J. et al. Assessment of ecological and hydro-geomorphological alterations under climate change using SWAT and IAHRIS in the Eo River in Northern Spain. **Water (Switzerland)**, v. 12, n. 6, 1 jun. 2020.

PINIEWSKI, M. et al. Responses of fish and invertebrates to floods and droughts in Europe. **Ecohydrology**, v. 10, n. 1, p. e1793, 2017.

POFF, N. L. A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. **Freshwater Biology**. [s.l: s.n.].

POFF, N. L. AND MATTHEWS, J. H. Environmental flows in the Anthropocence: past progress and future prospects. **Current Opinion in Environmental Sustainability**, 5:667–675, 2013.

POFF, N. L. AND ZIMMERMAN, J. K. H. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. **Freshwater Biology**, v. 55, n. 1, p. 194–205, 2010.

POFF, N. L. et al. River Flows and Water Wars: Emerging Science for Environmental Decision Making. **Ecology and the Environment**, Vol. 1, No. 6, pp. 298-306, 2003.

POFF, N. L. et al. The ecological limits of hydrologic alteration (ELOHA): A new framework for developing regional environmental flow standards. **Freshwater Biology**, v. 55, n. 1, p. 147–170, jan. 2010.

REITBERGER, B.; MCCARTNEY, M. Concepts of Environmental Flow Assessment and Challenges in the Blue Nile Basin, Ethiopia. In: **Nile River Basin**. [s.l.] Springer Netherlands, p. 337–358, 2011.

RICHTER, B. D. et al. How much water does a river need? **Freshwater Biology**, 37(1), 231–249, 1997. doi:10.1046/ j.1365-2427.1997.00153.x.

RICHTER, B. D. et al. A spatial assessment of hydrologic alteration within a river network. **Regul. Rivers: Res. Mgmt**, 14, 329-340, 1998.

RODRIGUES, J. A. M. et al. Climate change impacts under representative concentration pathway scenarios on streamflow and droughts of basins in the Brazilian Cerrado biome. **International Journal of Climatology**, v. 40, n. 5, p. 2511–2526, 1 abr. 2020.

ROLLS, R. J.; LEIGH, C.; SHELDON, F. Mechanistic effects of low-flow hydrology on riverine ecosystems: ecological principles and consequences of alteration. **Freshwater Science.** V (31), Issue 4, p 1163 – 1186, 2012.

SARTORI, A.; NETO, F. L.; GENOVEZ, A. M. Classificação hidrológica de solos brasileiros para a estimativa da chuva excedente com o método do serviço de conservação do solo dos Estados Unidos parte 1: classificação. **RBRH**, v. 10, n. 4, p. 5–18, 2005.

SAXTON, K. E.; RAWLS, W. J. Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. **Soil Science Society of America Journal**, v. 70, n. 5, p. 1569–1578, 9 2006. ISSN 03615995. Disponível em: <http://doi.wiley.com/10.2136/sssaj2005.0117>.

SCHUPFNER M, WIENERS K-H, WACHSMANN F, et al (2019) DKRZ MPI-ESM1.2-HR model output prepared for CMIP6 ScenarioMIP ssp585.

SEGALLA, M. V. et al. List of Brazilian amphibians. **Herpetologia Brasileira**, v. 10, n. 1, p. 121-216, 2021.

SHAFROTH, P. B. et al. Ecosystem effects of environmental flows: Modelling and experimental floods in a dryland river. **Freshwater Biology**, v. 55, n. 1, p. 68–85, jan. 2010.

SIDDIQUI, S. F. et al. Classifying flow regimes of the Amazon basin. **Aquatic Conservation: Marine and Freshwater Ecosystems**, v. 31, n. 5, p. 1005–1028, 1 maio 2021.

SILVA-SANTOS P. et al. Natural and anthropogenic variations in a channelized water course in Centre of Portugal. **Limnetica**. 23: 257–270, 2004.

SOLBRIG, O. T. The diversity of the savanna ecosystem. In: O . T. Solbrig, E. Medina, and J. F. Silva (Eds.). **Biodiversity and savanna ecosystem processes: a global perspective**. Springer-Verlag, Berlin, Germany, pp. 1-27, 1996.

SONE, J. S. et al. Water provisioning improvement through payment for ecosystem services. **Science of the Total Environment**, v. 655, p. 1197–1206, 10 mar. 2019.

SONE, J. S. et al. Water Security in an Uncertain Future: Contrasting Realities from an Availability-Demand Perspective. **Water Resources Management**, v. 36, n. 8, p. 2571–2587, 1 jun. 2022.

SPERA, S. A. et al. Land-use change affects water recycling in Brazil's last agricultural frontier. **Global change biology**, v. 22, n. 10, p. 3405–3413, 1 out. 2016.

The Nature Conservancy. Ecological Limits of Hydrologic Alteration (ELOHA). In: < http://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/ELOHA/Pages/ecological-limits-hydrolo.aspx>. Accessed: 13 Jan 2023.

The Nature Conservancy, 2009. Indicators of Hydrologic Alteration Version 7.1 User's Manual.

UNESCO; UN-Water. United Nations World Water Development Report 2020: Water and Climate Change. Paris, France: UNESCO; 2020. Report No.: ISBN: 978-92-3-100371-4.

United Nations Office for Disaster Risk Reduction (UNISDR) and Centre for Research on the Epidemiology of Disasters (CRED). Economic Losses, Poverty & Disasters (1998–2017). 2018.

VALLE JUNIOR, L.C.G., OLIVEIRA, P.T.S., RODRIGUES, D.B.B., 2019. Initial abstraction ratio and curve number estimation using rainfall and runoff data from a tropical watershed. **Rev. Bras. Recur. Hidr.** Disponível em: <https://doi.org/10.1590/2318-0331.241920170199>.

VOLODIN E, MORTIKOV E, GRITSUN A, et al (2019a) INM INM-CM4-8 model output prepared for CMIP6 ScenarioMIP ssp245.

VOLODIN E, MORTIKOV E, GRITSUN A, et al (2019b) INM INM-CM5-0 model output prepared for CMIP6 CMIP historical.

WANG, X. et al. Analysis of multi-dimensional hydrological alterations under climate change for four major river basins in different climate zones. **Climatic Change**, v. 141,

n. 3, p. 483–498, 1 abr. 2016.

WIGLEY, T. M. L.; RAPER, S. C. B. **Interpretation of High Projections for Global-Mean WarmingNew Series**. [s.l: s.n.].

XAVIER, A. C.; KING, C. W.; SCANLON, B. R. Daily gridded meteorological variables in Brazil (1980-2013). **International Journal of Climatology**, John Wiley and Sons Ltd, v. 36, n. 6, p. 2644–2659, 5 2016. ISSN 08998418. Disponível em: <http://doi.wiley.com/10.1002/joc.4518>.

YUKIMOTO S. et al. The Meteorological Research Institute Earth System Model Version 2.0, MRI-ESM2.0: Description and Basic Evaluation of the Physical Component. Journal of the Meteorological Society of Japan Ser II 97:931–965, 2019. Disponível em: <https://doi.org/10.2151/jmsj.2019-051>.

ZHANG, Y. et al. Classification of flow regimes for environmental flow assessment in regulated rivers: The Huai river basin, China. **River Research and Applications**, v. 28, n. 7, p. 989–1005, set. 2012.

ZHANG, Z. et al. Assessment of Water Capacity and Availability from Unregulated Stream Flows Based on Ecological Limits of Hydrologic Alteration (ELOHA) Environmental Flow Standards. **River Research and Applications**, v. 32, n. 7, p. 1469–1480, 1 set. 2015.

APPENDIX

Table 5. Input data required to run the SWAT+ model

Data	Description	Resolution	Source
Digital Elevation Model	IKONOS image	10 m	HEroS/UFMS
Soil order	-	1:160,000	Grande and Águas Guariroba S/A (2008)
Soil characteristics	Soil depth, texture, and organic matter	Typical soil profile	Anache et al. (2015)
	Hydrological group		Sartori, Neto and Genovez (2005)
	Other soil parameters estimated by pedo-transfer functions		Saxton and Rawls (206)
Land use and land cover	Land use and land cover in 2014	30 m	MapBiomas
Streamflow	-	Daily	HEroS/UFMS
Climate	Precipitation	Daily	HEroS/UFMS, Xavier, King and Scanlon (2016), and ERA5
	Maximum and minimum temperature		Xavier, King and Scanlon (2016), and ERA5
	Wind speed at 2 m		
	Relative humidity		
	Surface net downward shortwave radiation		

Table 6. The multimodel ensemble was created by computing individual models, in daily temporal resolution, as described below.

CMPIs	Spatial resolution	Reference
CMCC-ESM2	1.3° x 0.9°	Lovato et al. (2021)
EC-Earth3	0.7° x 0.7°	EC-Earth (2019)
INM-CM4-8	2.0° x 1.5°	Volodin et al. (2019a)
INM-CM5-0	2.0° x 1.5°	Volodin et al. (2019b)
MPI-ESM1-HR	0.9° x 0.9°	Schupfner et al. (2019)
MRI-ESM2-0	1.1° x 1.1°	Yukimoto et al. (2019)
NCC-NorESM2-MM	0.9° x 1.25°	Bentsen et al. (2019)

Table 7. Summary of IHA parameters

IHA Parameter Group	Hydrologic Parameters	Ecosystem Influences
1. Magnitude of monthly water conditions	Mean or median value for each calendar month	· Habitat availability for aquatic organisms
		· Soil moisture availability for plants
		· Availability of water for terrestrial animals
		· Availability of food/cover for furbearing mammals
		· Reliability of water supplies for terrestrial animals
		· Access by predators to nesting sites
	Subtotal 12 parameters	· Influences water temperature, oxygen levels, photosynthesis in water column
2. Magnitude and duration of annual extreme water conditions	Annual minima, 1-day mean Annual minima, 3-day means Annual minima, 7-day means Annual minima, 30-day means Annual minima, 90-day means	· Balance of competitive, ruderal, and stress- tolerant organisms
	Annual maxima, 1-day mean Annual maxima, 3-day means Annual maxima, 7-day means Annual maxima, 30-day means Annual maxima, 90-day means	· Creation of sites for plant colonization
	Number of zero-flow days	· Structuring of aquatic ecosystems by abiotic vs. biotic factors
	Base flow index: 7-day minimum flow/mean flow for year	· Structuring of river channel morphology and physical habitat conditions
		· Soil moisture stress in plants
		· Dehydration in animals
		· Anaerobic stress in plants
		· Volume of nutrient exchanges between rivers and floodplains
		· Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments
		· Distribution of plant communities in lakes, ponds, floodplains
	Subtotal 12 parameters	· Duration of high flows for waste disposal, aeration of spawning beds in channel sediments
3. Timing of annual extreme water conditions	Julian date of each annual 1-day maximum	· Compatibility with life cycles of organisms
	Julian date of each annual 1-day minimum	· Predictability/avoidability of stress for organisms
		· Access to special habitats during reproduction or to avoid predation
		· Spawning cues for migratory fish

	Subtotal 2 parameters	· Evolution of life history strategies, behavioral mechanisms
4. Frequency and duration of high and low pulses	Number of low pulses within each water year	· Frequency and magnitude of soil moisture stress for plants
	Mean or median duration of low pulses (days)	· Frequency and duration of anaerobic stress for plants
	Number of high pulses within each water year	· Availability of floodplain habitats for aquatic organisms
	Mean or median duration of high pulses (days)	· Nutrient and organic matter exchanges between river and floodplain
		· Soil mineral availability
		· Access for waterbirds to feeding, resting, reproduction sites
	Subtotal 4 parameters	· Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
5. Rate and frequency of water condition changes	Rise rates: Mean or median of all positive differences between consecutive daily values	· Drought stress on plants (falling levels)
	Fall rates: Mean or median of all negative differences between consecutive daily values	· Entrapment of organisms on islands, floodplains (rising levels)
	Number of hydrologic reversals	· Desiccation stress on low mobility stream edge (varial zone) organisms
	Subtotal 3 parameters	
	Grand total 33 parameters	

Source: The Nature Conservancy (2009)

Table 8. Summary of EFC parameters

EFC Type	Hydrologic Parameters	Ecosystem Influences
1. Monthly low flows	Mean or median values of low flows during each calendar month	· Provide adequate habitat for aquatic organisms
		· Maintain suitable water temperatures, dissolved oxygen, and water chemistry
		· Maintain water table levels in floodplain, soil moisture for plants
		· Provide drinking water for terrestrial animals
		· Keep fish and amphibian eggs suspended
		· Enable fish to move to feeding and spawning areas
	Subtotal 12 parameters	· Support hyporheic organisms (living in saturated sediments)
2. Extreme low flows	Frequency of extreme low flows during each water year or season	· Enable recruitment of certain floodplain plant species
	Mean or median values of extreme low flow event:	· Purge invasive, introduced species from aquatic and riparian communities
	· Duration (days)	· Concentrate prey into limited areas to benefit predators

	· Peak flow (minimum flow during event)	
	· Timing (Julian date of peak flow)	
	Subtotal 4 parameters	
3. High flow pulses	Frequency of high flow pulses during each water year or season	· Shape physical character of river channel, including pools, riffles
	Mean or median values of high flow pulse event:	· Determine size of streambed substrates (sand, gravel, cobble)
	· Duration (days)	· Prevent riparian vegetation from encroaching into channel
	· Peak flow (maximum flow during event)	· Restore normal water quality conditions after prolonged low flows, flushing away waste products and pollutants
	· Timing (Julian date of peak flow)	· Aerate eggs in spawning gravels, prevent siltation
	· Rise and fall rates	· Maintain suitable salinity conditions in estuaries
	Subtotal 6 parameters	
4. Small floods	Frequency of small floods during each water year or season	Applies to small and large floods:
	Mean or median values of small flood event:	· Provide migration and spawning cues for fish
	· Duration (days)	· Trigger new phase in life cycle (i.e., insects)
	· Peak flow (maximum flow during event)	· Enable fish to spawn in floodplain, provide nursery area for juvenile fish
	· Timing (Julian date of peak flow)	· Provide new feeding opportunities for fish, waterfowl
	· Rise and fall rates	· Recharge floodplain water table
		· Maintain diversity in floodplain forest types through prolonged inundation (i.e., different plant species have different tolerances)
		· Control distribution and abundance of plants on floodplain
	Subtotal 6 parameters	· Deposit nutrients on floodplain
5. Large floods	Frequency of large floods during each water year or season	Applies to small and large floods:
	Mean or median values of large flood event:	· Maintain balance of species in aquatic and riparian communities
	· Duration (days)	· Create sites for recruitment of colonizing plants
	· Peak flow (maximum flow during event)	· Shape physical habitats of floodplain
	· Timing (Julian date of peak flow)	· Deposit gravel and cobbles in spawning areas
	· Rise and fall rates	· Flush organism materials (food) and woody debris (habitat structures) into channel
		· Purge invasive, introduced species from aquatic and riparian communities
		· Disburse seeds and fruits of riparian plants

	· Drive lateral movement of river channel, forming new habitats (secondary channels, oxbow lakes)
Subtotal 6 parameters	· Provide plant seedlings with prolonged access to soil moisture
Grand total 34 parameters	

Source: The Nature Conservancy (2009)

Table 9. EFC parameters results

	EFC Parameters			
	Baseline	SSP2-4.5	SSP3-7.0	SSP5-8.5
Monthly Low flows				
January	6.86	6.60	6.86	6.78
February	7.45	6.62	7.14	7.48
March	7.14	6.85	6.73	7.41
April	6.51	6.43	6.37	7.15
May	6.35	6.50	6.43	6.54
June	6.32	6.59	6.50	6.45
July	6.16	6.47	6.37	6.24
August	5.77	6.36	6.30	5.92
September	5.61	6.01	6.11	5.65
October	5.39	5.74	5.80	5.43
November	5.34	5.68	5.75	5.37
December	5.94	6.25	6.21	6.17
Extreme Low Flows				
Peak	4.50	4.33	4.07	4.48
Duration	5.50	7	9	5
Timing	320.50	326.8	338	334
Frequency	0	0	0	0
High Flow Pulses				
Peak	10.20	9.75	9.79	10.18
Duration	8	6.5	6.5	7
Timing	1.25	3	361.5	1
Frequency	4	3	3	4
Rise rate	1.22	1.13	1.12	1.28
Fall rate	-0.63	-0.67	-0.64	-0.63
Small Floods				
Peak	16.35	16.55	16.45	16.30
Duration	91	111	111.30	67

Timing	26	43	32	25.50
Frequency	0	0	0	0
Rise rate	1.27	0.32	0.58	0.77
Fall rate	-0.08	-0.10	-0.14	-0.38
Large Floods				
Peak	19.10	20.55	21.1	20.45
Duration	173.50	231	214	167
Timing	49.50	43.5	36	39
Frequency	0	0	0	0
Rise rate	0.39	0.48	0.65	0.50
Fall rate	-0.08	-0.07	-0.08	-0.09

Source: Author

Table 10. IHA parameters results

	IHA Parameters			
	Baseline	SSP2-4.5	SSP3-7.0	SSP5-8.5
Parameter Group 1				
January	8.72	8.42	8.44	8.30
February	9.27	9.89	9.57	9.50
March	8.27	8.93	9.11	8.31
April	7.39	8.03	8.10	7.55
May	6.94	7.51	7.60	7.06
June	6.53	7.06	7.13	6.67
July	6.16	6.64	6.70	6.24
August	5.77	6.25	6.30	5.87
September	5.49	5.90	5.94	5.55
October	5.22	5.69	5.73	5.28
November	5.16	5.62	5.69	5.31
December	6.54	6.82	6.85	6.47
Parameter Group 2				
1-day minimum	4.82	5.21	5.27	4.91
3-day minimum	4.85	5.25	5.32	4.98
7-day minimum	4.93	5.32	5.39	5.05
30-day minimum	5.13	5.47	5.55	5.20
90-day minimum	5.31	5.71	5.77	5.35
1-day maximum	14.65	16.10	15.80	14.90
3-day maximum	13.35	14.90	14.50	13.82
7-day maximum	11.52	13.07	12.91	12.54
30-day maximum	10.02	10.77	10.65	10.51
90-day maximum	9	9.58	9.65	9.10

Number of zero days	0	0	0	0
Base flow index	0.72	0.71	0.73	0.72
Parameter Group 3				
Date of minimum	325.50	327.50	330	333
Date of maximum	28.50	37.50	34	35.50
Parameter Group 4				
Low pulse count	3	2	2	3
Low pulse duration	11.25	6	5	9.50
High pulse count	6	5	5	6
High pulse duration	4.25	4.25	4.5	4.5
Low Pulse Threshold	5.48			
High Pulse Threshold	7.97			
Parameter Group 5				
Rise rate	0.23	0.26	0.26	0.22
Fall rate	-0.02	-0.02	-0.02	-0.02
Number of reversals	78	74	73	72

Source: Author

Table 11. RVA results for SSP2-4.5

	Middle RVA Category			**High RVA Category**			**Low RVA Category**		
	Expected	Observed	HA	Expected	Observed	HA	Expected	Observed	HA
Group 1									
January	28.67	28	-0.02	28.67	23	-0.20	28.67	35	0.22
February	28.67	12	-0.58	28.67	46	0.60	28.67	28	-0.02
March	28.67	20	-0.30	28.67	48	0.67	28.67	18	-0.37
April	28.67	14	-0.51	28.67	49	0.71	28.67	23	-0.20
May	31.53	14	-0.56	28.67	49	0.71	25.80	23	-0.11
June	28.67	15	-0.48	28.67	48	0.67	28.67	23	-0.20
July	28.67	15	-0.48	28.67	48	0.67	28.67	23	-0.20
August	28.67	15	-0.48	28.67	48	0.67	28.67	23	-0.20
September	28.67	17	-0.41	28.67	46	0.60	28.67	23	-0.20
October	28.67	15	-0.48	28.67	47	0.64	28.67	24	-0.16
November	31.53	24	-0.24	28.67	40	0.39	25.80	22	-0.15
December	28.67	31	0.08	28.67	38	0.33	28.67	17	-0.41
Group 2									
1-day min	28.67	17	-0.41	28.67	45	0.57	28.67	24	-0.16
3-day min	28.67	16	-0.44	28.67	45	0.57	28.67	25	-0.13
7-day min	28.67	19	-0.34	28.67	42	0.46	28.67	25	-0.13
30-day min	28.67	18	-0.37	28.67	43	0.50	28.67	25	-0.13
90-day min	28.67	17	-0.41	28.67	44	0.53	28.67	25	-0.13
1-day max	28.67	27	-0.06	28.67	38	0.33	28.67	21	-0.27
3-day max	28.67	26	-0.09	28.67	40	0.39	28.67	20	-0.30
7-day max	28.67	25	-0.13	28.67	42	0.46	28.67	19	-0.34
30-day max	28.67	22	-0.23	28.67	40	0.39	28.67	24	-0.16
90-day max	28.67	21	-0.27	28.67	39	0.36	28.67	26	-0.09

Zero days	86	86	0	0	0		0	0	
Base flow index	28.67	24	-0.16	28.67	28	-0.02	28.67	34	0.19
Group 3									
Date of min	28.67	18	-0.37	28.67	32	0.12	28.67	36	0.26
Date of max	28.67	30	0.05	28.67	38	0.33	28.67	18	-0.37
Group 4									
Low pulse count	40.13	24	-0.40	17.20	17	-0.01	28.67	45	0.57
Low pulse duration	22.93	19	-0.17	22.93	8	-0.65	22.93	22	-0.04
High pulse count	60.20	34	-0.43	14.33	15	0.05	11.47	37	2.23
High pulse duration	48.73	30	-0.38	28.67	32	0.12	8.60	22	1.56
Group 5									
Rise rate	28.67	14	-0.51	28.67	56	0.95	28.67	16	-0.44
Fall rate	57.33	56	-0.02	8.60	6	-0.30	20.07	24	0.20
Number of reversals	31.53	27	-0.14	25.80	18	-0.30	28.67	41	0.43

Source: Author

Table 12. RVA results for SSP3-7.0

	Middle RVA Category			**High RVA Category**			**Low RVA Category**		
	Expected	Observed	HA	Expected	Observed	HA	Expected	Observed	HA
Group 1									
January	28.67	27	-0.06	28.67	24	-0.16	28.67	35	0.22
February	28.67	24	-0.16	28.67	41	0.43	28.67	21	-0.27
March	28.67	18	-0.37	28.67	48	0.67	28.67	20	-0.30
April	28.67	17	-0.41	28.67	47	0.64	28.67	22	-0.23
May	31.53	17	-0.46	28.67	47	0.64	25.8	22	-0.15
June	28.67	18	-0.37	28.67	47	0.64	28.67	21	-0.27
July	28.67	18	-0.37	28.67	47	0.64	28.67	21	-0.27
August	28.67	17	-0.41	28.67	47	0.64	28.67	22	-0.23
September	28.67	20	-0.30	28.67	45	0.57	28.67	21	-0.27
October	28.67	18	-0.37	28.67	46	0.60	28.67	22	-0.23
November	31.53	24	-0.24	28.67	42	0.46	25.8	20	-0.22
December	28.67	29	0.01	28.67	38	0.33	28.67	19	-0.34
Group 2									
1-day min	28.67	16	-0.44	28.67	47	0.64	28.67	23	-0.20
3-day min	28.67	15	-0.48	28.67	47	0.64	28.67	24	-0.16
7-day min	28.67	16	-0.44	28.67	46	0.60	28.67	24	-0.16
30-day min	28.67	16	-0.44	28.67	47	0.64	28.67	23	-0.20
90-day min	28.67	18	-0.37	28.67	47	0.64	28.67	21	-0.27
1-day max	28.67	29	0.01	28.67	34	0.19	28.67	23	-0.20
3-day max	28.67	25	-0.13	28.67	37	0.29	28.67	24	-0.16
7-day max	28.67	25	-0.13	28.67	40	0.39	28.67	21	-0.27
30-day max	28.67	23	-0.20	28.67	40	0.39	28.67	23	-0.20
90-day max	28.67	21	-0.27	28.67	40	0.39	28.67	25	-0.13
Number of zero days	86	86	0	0	0		0	0	

Base flow index	28.67	31	0.08	28.67	33	0.15	28.67	22	-0.23
Group 3									
Date of min	28.67	26	-0.09	28.67	33	0.15	28.67	27	-0.06
Date of max	28.67	37	0.29	28.67	26	-0.09	28.67	23	-0.20
Group 4									
Low pulse count	40.13	21	-0.48	17.20	21	0.22	28.67	44	0.53
Low pulse duration	22.93	14	-0.39	22.93	7	-0.69	22.93	31	0.35
High pulse count	60.20	39	-0.35	14.33	14	-0.02	11.47	33	1.88
High pulse duration	48.73	31	-0.36	28.67	37	0.29	8.6	16	0.86
Group 5									
Rise rate	28.67	21	-0.27	28.67	46	0.60	28.67	19	-0.34
Fall rate	57.33	54	-0.06	8.60	5	-0.42	20.07	27	0.34
Number of reversals	31.53	14	-0.56	25.80	24	-0.07	28.67	48	0.67

Source: Author

Table 13. RVA results for SSP5-8.5

	Middle RVA Category			**High RVA Category**			**Low RVA Category**		
	Expected	Observed	HA	Expected	Observed	HA	Expected	Observed	HA
Group 1									
January	28.67	27	-0.06	28.67	24	-0.16	28.67	35	0.22
February	28.67	24	-0.16	28.67	38	0.33	28.67	24	-0.16
March	28.67	35	0.22	28.67	37	0.29	28.67	14	-0.51
April	28.67	35	0.22	28.67	32	0.12	28.67	19	-0.34
May	31.53	36	0.14	28.67	31	0.08	25.80	19	-0.26
June	28.67	36	0.26	28.67	31	0.08	28.67	19	-0.34
July	28.67	35	0.22	28.67	32	0.12	28.67	19	-0.34
August	28.67	35	0.22	28.67	31	0.08	28.67	20	-0.30
September	28.67	36	0.26	28.67	30	0.05	28.67	20	-0.30
October	28.67	35	0.22	28.67	31	0.08	28.67	20	-0.30
November	31.53	35	0.11	28.67	31	0.08	25.80	20	-0.22
December	28.67	28	-0.02	28.67	35	0.22	28.67	23	-0.20
Group 2									
1-day min	28.67	35	0.22	28.67	30	0.05	28.67	21	-0.27
3-day min	28.67	34	0.19	28.67	30	0.05	28.67	22	-0.23
7-day min	28.67	34	0.19	28.67	30	0.05	28.67	22	-0.23
30-day min	28.67	34	0.19	28.67	31	0.08	28.67	21	-0.27
90-day min	28.67	36	0.26	28.67	30	0.05	28.67	20	-0.30
1-day max	28.67	36	0.26	28.67	27	-0.06	28.67	23	-0.20
3-day max	28.67	31	0.08	28.67	32	0.12	28.67	23	-0.20
7-day max	28.67	29	0.01	28.67	35	0.22	28.67	22	-0.23
30-day max	28.67	31	0.08	28.67	29	0.01	28.67	26	-0.09
90-day max	28.67	31	0.08	28.67	29	0.01	28.67	26	-0.09
Number of zero days	86	86	0	0	0		0	0	

Base flow index	28.67	39	0.36	28.67	13	-0.55	28.67	34	0.19
Group 3									
Date of minimum	28.67	18	-0.37	28.67	41	0.43	28.67	27	-0.06
Date of maximum	28.67	28	-0.02	28.67	32	0.12	28.67	26	-0.09
Group 4									
Low pulse count	40.13	30	-0.25	17.20	21	0.22	28.67	35	0.22
Low pulse duration	22.93	24	0.05	22.93	12	-0.48	22.93	22	-0.04
High pulse count	60.20	42	-0.30	14.33	18	0.26	11.47	26	1.27
High pulse duration	48.73	43	-0.12	28.67	28	-0.02	8.60	15	0.74
Group 5									
Rise rate	28.67	19	-0.34	28.67	34	0.19	28.67	33	0.15
Fall rate	57.33	55	-0.04	8.60	10	0.16	20.07	21	0.05
Number of reversals	31.53	19	-0.40	25.80	19	-0.26	28.67	48	0.67

Source: Author

Figure 10. Daily evapotranspiration on SSP2-4.5 scenario by Swat+ model. Figure shows (a) Immediate Future (2015-1040), (b) Intermediate Future (2041-2070) and (c) Distant Future (2071-2100).

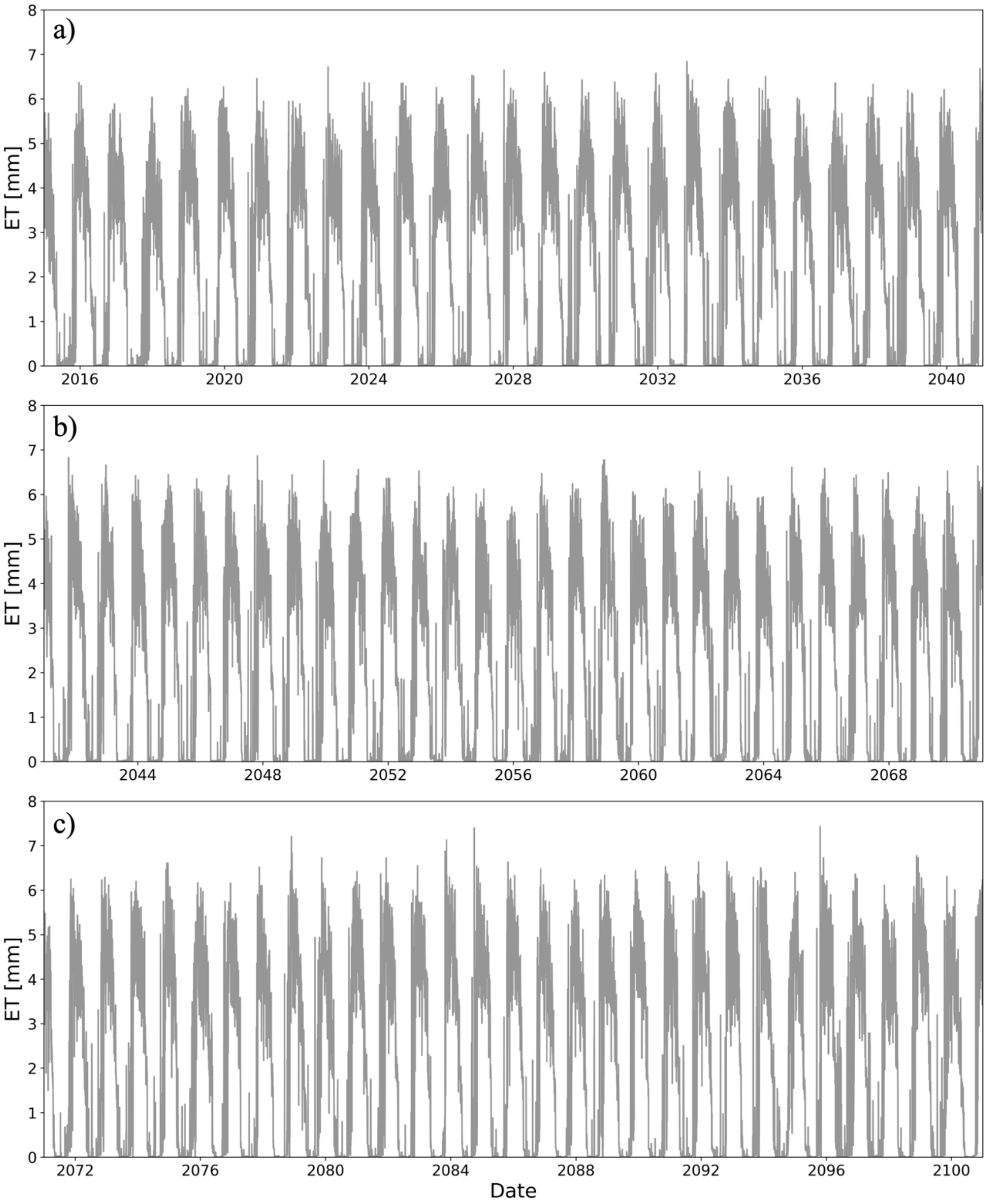


Figure 11. Daily evapotranspiration on SSP3-7.0 scenario by Swat+ model. Figure shows (a) Immediate Future (2015-1040), (b) Intermediate Future (2041-2070) and (c) Distant Future (2071-2100).

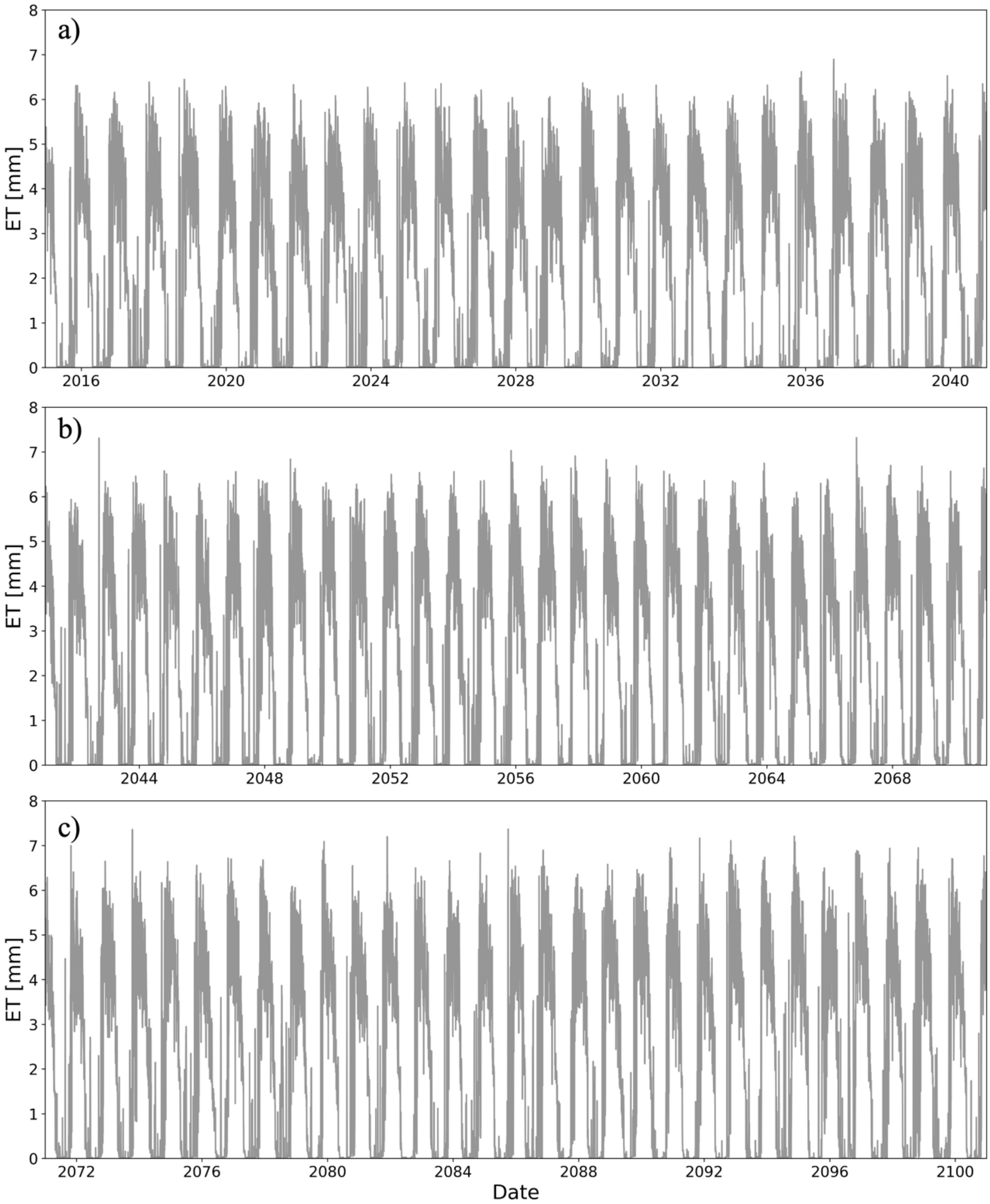


Figure 12. Daily evapotranspiration on SSP5-8.5 scenario by Swat+ model. Figure shows (a) Immediate Future (2015-1040), (b) Intermediate Future (2041-2070) and (c) Distant Future (2071-2100).