

Projected effects of climate change in precipitation and streamflows of the Upper Orinoco River Basin from global and regional climate models

Hernán D. Salas ^{a,b,*}, Alejandro Builes-Jaramillo ^b, Carolina Florian ^b, Juliana Valencia ^b, Yesid Tamayo^b, Mariana Bermúdez^b, Melissa Rodríguez^b and Katherine Echeverri^b

^a Facultad de Ciencias Exactas y Aplicadas, Instituto Tecnológico Metropolitano, Calle 73 No. 76A – 354, Medellín, Antioquia 050034, Colombia

^b Facultad de Arquitectura e Ingeniería, Institución Universitaria Colegio Mayor de Antioquia, Carrera 78 # 65-46 Bloque Fundacional piso 2, Medellín, Antioquia 050034, Colombia

*Corresponding author. E-mail: hernansalas@itm.edu.co

 HDS, 0000-0002-6182-237X; AB-J, 0000-0002-3474-6922; CF, 0000-0003-1807-1379; JV, 0000-0002-8590-8821

ABSTRACT

We studied the projections of streamflows under climate change scenarios in the Upper Orinoco River Basin by using precipitation from 15 global and regional climate models for the period 2020–2099. For this purpose, we calibrated and validated a hydrological model with a very good performance. Our results show that both precipitation and streamflow have a significant reduction for the RCP8.5 scenario that ranges from 5 and 7% in relation to the long-term means at the end of the century. The changes in both variables are not significant for the RCP2.6 scenario. Moreover, we compute several indicators of change in the streamflow to quantify alterations in high-, mid-, and low-range flows. Our results suggest that the main alterations for the future runoff would be evidenced in the mid-range and low flows, which could increase around ~5 and ~25%, respectively. These alterations could lead to changes in the hydrological, environmental, and ecological balance of the basin. This work provides information regarding the possible effects of climate change on the streamflow of one of the most important river basins of northern South America, which is pivotal for supporting future decision-making on water supply for social, environmental, and productive sectors.

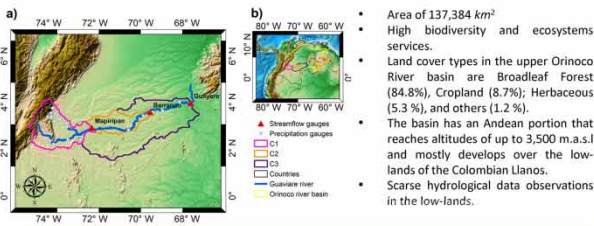
Key words: future scenarios, GCMs, global warming, hydrological modeling, rainfall–runoff, RCMs, river flows

HIGHLIGHTS

- Projections suggest that streamflow decreases under climate change scenarios in the Upper Orinoco River Basin according to climate models.
- Our work sheds new light on precipitation trends and streamflow modeling in the tropics by incorporating the most recent climate models.
- Given the Orinoco River Basin's social and economic activities, this research provides useful information for sustainable water resources and management.

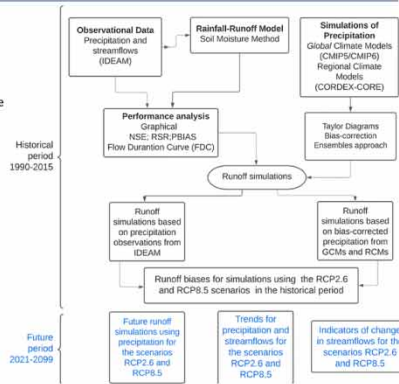
GRAPHICAL ABSTRACT

Upper Orinoco River Basin

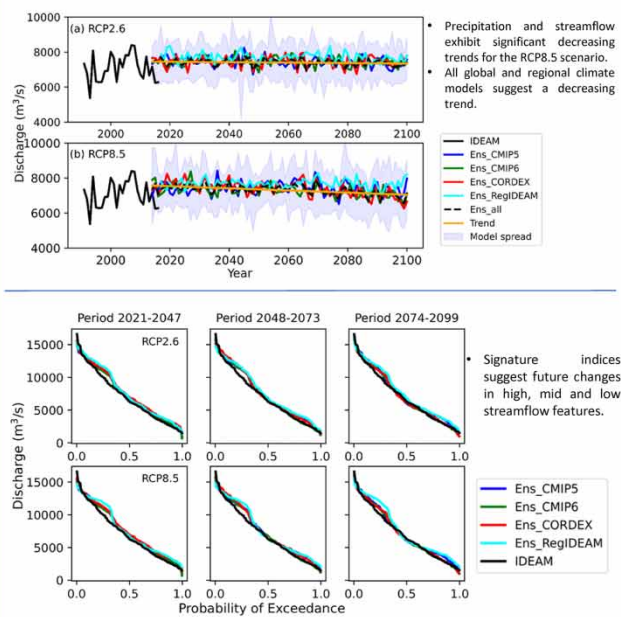


Methodological Scheme

- Datasets
- Global and Regional Climate Models
- Hydrological modeling
- Projected streamflow simulations



Main Results



1. INTRODUCTION

The Orinoco River Basin has an area of approximately $1.0 \times 10^6 \text{ km}^2$ and a discharge of $3.5 \times 10^4 \text{ m}^3 \text{ s}^{-1}$, making it the third biggest basin in South America, with around 70 and 30% continental territory belonging to Venezuela and Colombia, respectively. This river basin also has the third highest discharge in the world (López *et al.* 2012). The basin is divided into three parts: the Alto Orinoco, located in the south, with the Ventuari river as the main tributary; the Medio Orinoco, mainly located in the Colombian Orinoco region, with tributaries such as the Inírida, Vichada, Guaviare, Meta, and Arauca; and finally, the Bajo Orinoco, near the delta, with the Caroni and the Caura as the most important tributaries (Silva León 2005; Frappart *et al.* 2012). Furthermore, this river basin shares a border with the Amazon River Basin, and both basins are the main sources of Andean sediments and dissolved elements in the Atlantic Ocean (Meade 2008; Mora *et al.* 2020). The Orinoco River Basin exhibits tremendous ecological heterogeneity due to its location between the northern Andes, Caribbean Mountain ranges, the Guianese shield, and the development of the low relief areas known as Llanos in both countries (Warne *et al.* 2002; Frappart *et al.* 2012).

General circulation models (GCMs) have been used to represent and evaluate the possible impacts of increased atmospheric concentrations of greenhouse gases and anthropogenic aerosols (Edwards 2011; IPCC 2022). The Coupled Model Intercomparison Project (CMIP), in its fifth and sixth phases (CMIP5 and CMIP6), presents the most recent advances to contribute to the understanding of the climate system and its responses to human activities (Taylor *et al.* 2012; Eyring *et al.* 2016). However, these models have limitations due to their systematic biases, coarse spatial resolution, and lack of representation of climatic processes at regional scales (Arias *et al.* 2021; Builes-Jaramillo & Pántano 2021). On the other hand, regional climate models (RCMs) calculate mass and energy balance at a finer resolution than GCMs, a process referred to as dynamical downscaling (Giorgi 2019; Giorgi *et al.* 2021; Brêda *et al.* 2022). Some authors argue that RCMs add value to GCMs because they offer a finer representation of regional climatic processes (Falco *et al.* 2019; Llopart *et al.* 2020; Ciarlo' *et al.* 2021), which are important for assessing hydrological impacts (Teutschbein & Seibert 2012; Lee *et al.* 2019). Although RCMs are valuable tools for regional impact studies of climate change, their uncertainties should be acknowledged beforehand (Hawkins & Sutton 2009; Foley 2010; Brêda *et al.* 2022). To address these uncertainties, diverse techniques of bias correction (Christensen *et al.* 2008; Teutschbein & Seibert 2012; Muerth *et al.* 2013) or/and ensemble approaches (Hagedorn *et al.* 2005; Semenov & Stratonovitch 2010; Díaz *et al.* 2021) have been used in data from RCMs and GCMs.

In the last few decades, several authors have stated that factors such as human intervention in catchments, the impact of low-frequency variability, and human-induced climate change are the primary drivers of alterations in the water cycle, as well as the magnitude and frequency of floods (Perreault *et al.* 1999; Zhang & Schilling 2006; Villarini *et al.* 2009). Recently, the Intergovernmental Panel on Climate Change's Sixth Assessment Report (AR6) (IPCC 2022) has also concluded that human activities play a crucial role in diagnosing and understanding climate change, particularly in terms of its impacts, adaptation, and vulnerability. To better understand hydrologic phenomena and assess the effects of climate change on the hydrological cycle, researchers have used rainfall-runoff models (Jiang *et al.* 2007; Moradkhani & Sorooshian 2009; Chawla & Mujumdar 2015; Amanambu *et al.* 2019; Chu *et al.* 2019; Zeng *et al.* 2020; Carvalho *et al.* 2022; Chathuranika *et al.* 2022; Zhang *et al.* 2022; Salas *et al.* 2023). For instance, Pimentel *et al.* (2021) used a coupled hydrological model to study the Orinoco region of Colombia, considering the rain runoff process, the river-floodplain interaction, and anthropic processes such as surface water extraction and groundwater extraction. They analyzed five different agro-industrial expansion scenarios and found that the Colombian Orinoco could face significant pressure on water resources, leading to critical changes in the water availability regime.

The scenarios showed reductions of up to 85% in low water flows in over 50% of the Colombian Orinoco Basin area. In the most extreme scenarios, the Meta, Vichada, and Guaviare rivers could experience reductions of 95, 98, and 50% in low water flows, respectively. However, this study only focused on effects of changes in land cover on the streamflow and did not consider the possible effects of precipitation changes under climate change scenarios. It is worth noting that the Upper Orinoco in Colombia connects the Andes Mountain range and the Llanos plains, which are shared by Colombia and Venezuela (Meade 2008; Frappart *et al.* 2014). This region must balance deforestation, human pressure, and conservation efforts after the peace treaty in Colombia (Clerici *et al.* 2020; Rodríguez-de Francisco *et al.* 2021).

Hence, we analyzed the future projected precipitation and streamflow in the upper Orinoco River Basin addressing the following questions: (1) Does monthly precipitation over the basin exhibit changes in trends for the future scenarios RCP2.6 and RCP8.5?; (2) Do the simulated monthly streamflow over the basin exhibit changes in terms of trends and exceedance probabilities for the future scenarios RCP2.6 and RCP8.5?; (3) Is there an agreement for future projected precipitation provided by the different global and RCMs for the RCP2.6 and RCP8.5 scenarios?; and (4) What are the possible impacts on the streamflow according to projected precipitation by different RCP scenarios?

2. REGION OF STUDY

The Upper Orinoco River Basin has an area of 137,384 km² and is also referred to as the Guaviare River Basin. The basin has an Andean portion that reaches altitudes of up to 3,500 m.a.s.l. and mostly develops over the low-lands of the Colombian Llanos (see Figure 1). It has high biodiversity and ecosystems services (Frappart *et al.* 2014; Lasso *et al.* 2016), which can also be evidenced according to the Nature Map Earth project (<https://explorer.naturemap.earth/map>). The upper Orinoco is the epicenter of transit for small and cargo transport ships, tourism, fishing, adventure, rest, and contemplation. However, it is also one of the most compromised regions of Colombia in terms of deforestation (De Los Rios 2022), armed conflict (Ganzenmüller *et al.* 2022), and conservation (Zamudio & Maldonado-Ocampo 2022). Figure 1 shows the study region in the context of the Orinoco River Basin and northern South America. Figure 1(a) specifically shows the upper Orinoco River Basin, which is in the southeastern continental territory of Colombia. Figure 1(b) shows the location of the study region in the context of northern South America, including the Orinoco River Basin. According to the Global Land Cover by National Mapping Organizations (GLCNMO) (Kobayashi *et al.* 2017), the land cover types in the upper Orinoco River Basin are Broadleaf Forest (84.8%), Cropland (8.7%); Herbaceous (5.3%), and others (1.2%).

3. DATA

3.1. Observational data

We used time series at monthly temporal resolution for precipitation and streamflow provided by the Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM for its Spanish acronym). Specifically, we used 20 time series with precipitation records and 3 time series with streamflow records for the common period 1990–2015 (26 years record length). We use time series for both variables considering less than 10% missing data in the time series. The missing values were replaced with the 26-year average of the existing monthly data. To clarify, any missing data point for a given month i in year j represented by $X_{i,j}$ was replaced with the monthly average $\langle X_{i,j} \rangle$ calculated over a 26-year period for each precipitation and streamflow gauge,

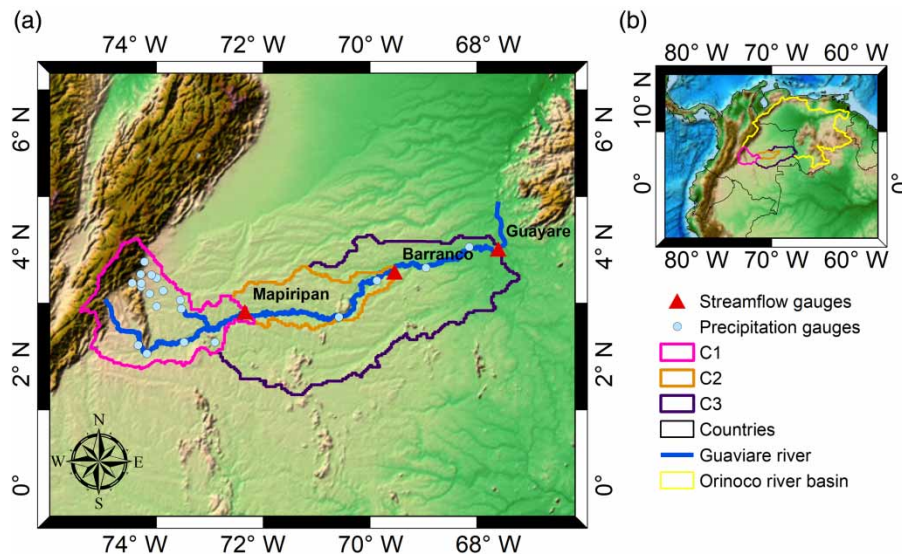


Figure 1 | Region of study. (a) Upper Orinoco River Basin. (b) Continental context of the region of study including the Orinoco River basin (yellow line).

where $\langle \cdot \rangle$ denotes the daily average. Then, these time series of streamflows and precipitation are used in the semi-distributed rainfall–runoff model (see Section 4.2). In this work, we will show results (Section 5) only for the streamflow gauge Guayare, which is located at the outlet of the basin. Data are freely available at <https://dhime.ideam.gov.co/>.

In addition, we use the GLCNMO dataset, which was developed by the International Steering Committee for Global Mapping (ISCGM) in collaboration with the Geospatial Information Authority of Japan (GSI), Chiba University, and NGIAs of respective countries and regions. In this work, we use the third version that uses MODIS data 2013 (Terra & Aqua) combined with remote sensing technology (Kobayashi *et al.* 2017).

3.2. GCMs and RCMs

We use precipitation provided by the global climate models from the CMIP5 and CMIP6 experiments (Eyring *et al.* 2016) as well as RCMs from the CORDEX-CORE experiment, which are available in the Earth System Grid Federation web page ESFG-<https://esgf-node.llnl.gov/projects/esgf-llnl>, for the 1990–2015 period and for two future forcing scenarios. In this way, we used the Representative Concentration Pathways (RCPs) RCP2.6 and RCP8.5 from CMIP5 and CORDEX-CORE, as well as the Shared Socioeconomic Pathways (SSPs) SSP1-2.6 and SSP5-8.5 from CMIP6. Since RCP2.6 and RCP8.5 are comparable to SSP1-2.6 and SSP5-8.5 in terms of radioactive forcing, respectively (Riahi *et al.* 2017), hereafter we use the terminology RCP2.6 and RCP8.5 for all of them. Table 1 shows some general information about climate models that provide precipitation projections for the region of study and that exhibit a good performance over northern South America according to Arias *et al.* (2021). Moreover, we use the regionalization of precipitation for the CMIP5 models provided by IDEAM (hereafter referred to as RegIDEAM) which is available at <http://www.ideam.gov.co/web/tiempo-y-clima/escenarios-cambio-climatico>.

4. METHODS

4.1. Indicators of change in the streamflow

We simulate runoff using precipitation data from GCMs and RCMs for historic and future periods using the RCP2.6 and RCP8.5 scenarios. Furthermore, we quantify trends using Kendall's non-parametric test (Kendall 1975) for a monotonic trend using the Theil-Sen method (Sen 1968) to estimate the slope, confidence intervals, and significance test. Moreover, we quantify changes in the probability of exceedance curves of the streamflow (commonly referred to as Flow Duration Curve or FDC) between historical observations and simulations for the periods 2020s (2021–2047), 2050s (2048–2073), and 2080s (2074–2099), as was recently used by Chathuranika *et al.* (2022).

Table 1 | Description of global climate models (GCMs) and regional climate models (RCMs)

Project	Model	Institute	Lon. Lat. res.	Energy	References
CMIP5	HadGEM2-ES	Met Office Hadley Centre(UK)	1.875×1.25	RCP2.6;RCP8.5	Jones <i>et al.</i> (2011)
	MIROC5	Atmosphere and Ocean Research Institute National Institute for Environmental Studies Japan Agency for Marine-Earth Science and Technology	1.4×1.4	RCP2.6;RCP8.5	Watanabe <i>et al.</i> (2010)
	MPI-ESM-LR	Max Planck Institute for Meteorology	1.88×1.88	RCP2.6;RCP8.5	Zanchettin <i>et al.</i> (2013)
	NorESM1-M	Norwegian Climate Center	2.5×1.9	RCP2.6;RCP8.5	Zhang <i>et al.</i> (2012)
	NorESM1-ME	Norwegian Climate Center	2.5×1.9	RCP2.6;RCP8.5	Tjiputra <i>et al.</i> (2013)
CMIP6	EC-Earth3	European research consortium Ec-Earth	0.70×0.70	RCP2.6;RCP8.5	Döscher <i>et al.</i> (2022)
	EC-Earth3-Veg	European research consortium Ec-Earth	0.70×0.70	RCP2.6;RCP8.5	Döscher <i>et al.</i> (2022)
	MPI-ESM1-2-HR	Max Planck Institute for Meteorology	0.93×0.93	RCP2.6;RCP8.5	Gutjahr <i>et al.</i> (2019)
	FGOALS-g3	Institute of Atmospheric Physics, Chinese Academy of Sciences	2×2.25	RCP2.6;RCP8.5	Li <i>et al.</i> (2020)
	NorESM2-MM	Norwegian Climate Center	1.25×0.93	RCP2.6;RCP8.5	Seland <i>et al.</i> (2020)
CORDEX	HadGEM2-ES-REMO	Met Office Hadley	0.25×0.25	RCP2.6;RCP8.5	Bellouin <i>et al.</i> (2011)
	NorESM1-M-REMO	Norwegian Climate Center	0.25×0.25	RCP2.6;RCP8.5	Bentsen <i>et al.</i> (2013)
	MPI-ESM-LR-REMO	Max Planck Institute for Meteorology	0.25×0.25	RCP2.6;RCP8.5	Jungclaus <i>et al.</i> (2013)
	MPI-ESM-MR-RegCM4	Max Planck Institute for Meteorology	0.25×0.25	RCP2.6;RCP8.5	Jungclaus <i>et al.</i> (2013)
	NorESM1-M-RegCM4	Norwegian Climate Center	0.25×0.25	RCP2.6;RCP8.5	Bentsen <i>et al.</i> (2013)

Here, we use the FDC to compare the streamflow simulations for the previously defined periods (2020s, 2050s, and 2080s) as well as simulated streamflow for the RCP scenarios (RCP2.6 and RCP8.5). Based on the works by Casper *et al.* (2012), we carried out a comparative analysis using the following indicators of change in the streamflow:

$$BiasRR = \frac{mean(FDC_s) - mean(FDC_o)}{mean(FDC_o)} * 100 \quad (1)$$

$$BiasFMM = \frac{median(FDC_s) - median(FDC_o)}{median(FDC_o)} \quad (2)$$

$$BiasFDCmidslope = \frac{(\log(FDC_{s,0.20}) - \log(FDC_{s,0.70})) - (\log(FDC_{o,0.20}) - \log(FDC_{o,0.70}))}{(\log(FDC_{o,0.20}) - \log(FDC_{o,0.70}))} * 100 \quad (3)$$

$$BiasFHV = \frac{\int_0^{0.10} FDC_{s,p} dp - \int_0^{0.10} FDC_{o,p} dp}{\left(\int_0^{0.10} FDC_{s,p} dp \right)} \quad (4)$$

$$BiasFLV = \frac{\int_{0.7}^{1.0} (\log(FDC_{s,p}) - \log(Q_{min s})) dp - \int_{0.7}^{1.0} (\log(FDC_{o,p}) - \log(Q_{min o})) dp}{\int_{0.7}^{1.0} (\log(FDC_{o,p}) - \log(Q_{min o})) dp} * 100 \quad (5)$$

where $Q_{min s}$ and $Q_{min o}$ are the minimum value of FDC_s and FDC_o .

$$DiffQ95 = \frac{mean(FDC_{s,95}) - mean(FDC_{o,95})}{mean(FDC_{o,95})} * 100 \quad (6)$$

where signature index is defined as follows being $FDC_{o,p}$ and $FDC_{s,p}$ the observed and simulated FDCs of the streamflow and p the probability of exceedance.

4.2. Rainfall–runoff model

We use the Soil Moisture Method (hereafter SMM) presented by [Yates *et al.* \(2005\)](#), which computes the water changes within the soil moisture zone using a 2-storage soil water accounting scheme that considers precipitation, runoff, and actual evapotranspiration (Ev), while using potential evapotranspiration (PET) to drive the extraction of water from the soil moisture.

Furthermore, the SMM uses empirical functions that describe evapotranspiration, surface runoff, sub-surface runoff or interflow, and deep percolation ([Yates *et al.* 2005](#)). [Figure 2](#) shows a schematic representation of the SMM model and its equations:

$$S_{wj} \frac{dz_{1,j}}{dt} = P_e(t) - PET(t)k_{c,j}(t) \left(\frac{5z_{1,j} - 2z_{1,j}^2}{3} \right) - P_e(t)z_{1,j}^{LA_{I_i}/2} - f_i k_j z_{1,j}^2 - (1 - f_j)k_j z_{1,j}^2 \quad (7)$$

$$Dw_j \frac{dz_{2,j}}{dt} = (1 - f_j)k_s z_{1,j}^2 - k_d z_{2,j}^2 \quad (8)$$

where P_e is the effective precipitation, $z_{1,j}$ and $z_{2,j}$ denote the relative soil water storage as a fraction of the total effective storage ranging between 0 and 1, where 0 represents permanent wilting point and 1 means field capacity. S_{wj} denotes an estimate

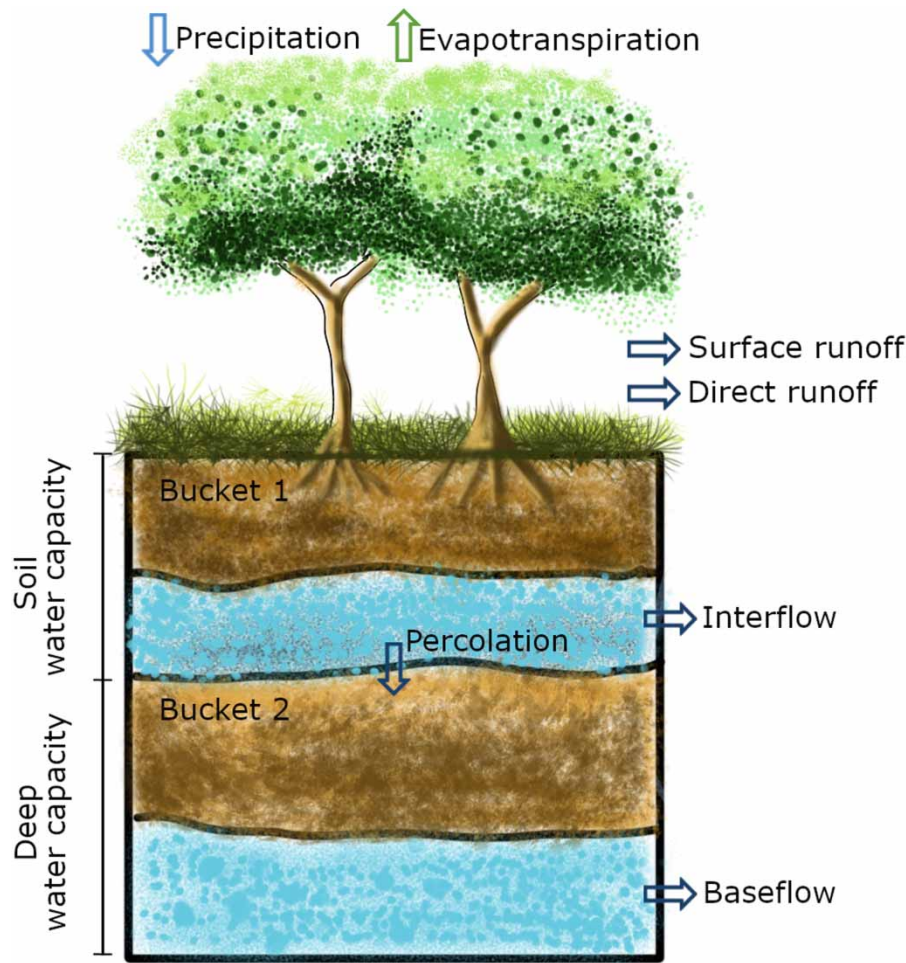


Figure 2 | Schematic representation of the soil moisture model proposed by [Yates *et al.* \(2005\)](#).

of the soil water holding capacity (in mm) for each land cover fraction, j . PET is the Penman–Montieth reference crop potential evapotranspiration (in mm/day) and $k_{c,j}$ is the crop/plant coefficient for each fractional cover. The Leaf and Stem Area Index (LAI) is assigned to the land cover class, the lowest LAI _{j} corresponds to the highest surface runoff response, LAI is also denoted as Runoff Resistance Factor (RRF), which is dimensionless (Angarita *et al.* 2018). k_j denotes the upper storage conductivity (mm/time) and f_j is a quasi-physical tuning parameter related to soil, land cover type, and topography that fractionally partitions water either horizontally, f_j or vertically ($1 - f_j$). Figure 3 summarizes the methodology used in this work as a schematic flow chart.

4.2.1. Rainfall–runoff model structure

We use the SMM model incorporated as a semi-distributed rainfall–runoff model in the software Water Evaluation and Planning – WEAP (<https://www.weap21.org/>). Then, for the rainfall–runoff model implementation, we define three catchments or sub-areas in the river basin, which are denoted as C1, C2, and C3 (see Figure 1), which have the types of Land Covers shown by percentage in Table 2. For each catchment, we characterize the types of land cover and assign the parameters of the model, to establish the representative time series of precipitation (C1, C2, and C3 have 16, 1, and 3 rain gauges, respectively), and the streamflow gauges at the output of each sub-area (see Figure 1). In particular, the parameters related to surface runoff (RRF and K_c) are assigned for each type of land cover, whereas the parameters associated with sub-surface runoff, interflow, and deep percolation (Dw , f , Sw , k_s , k_d , z_1 , z_2), are selected as a unique value for all catchments and land covers because of the lack of sub-surface runoff, interflow, and deep percolation observational data. Moreover, we use random sampling to obtain

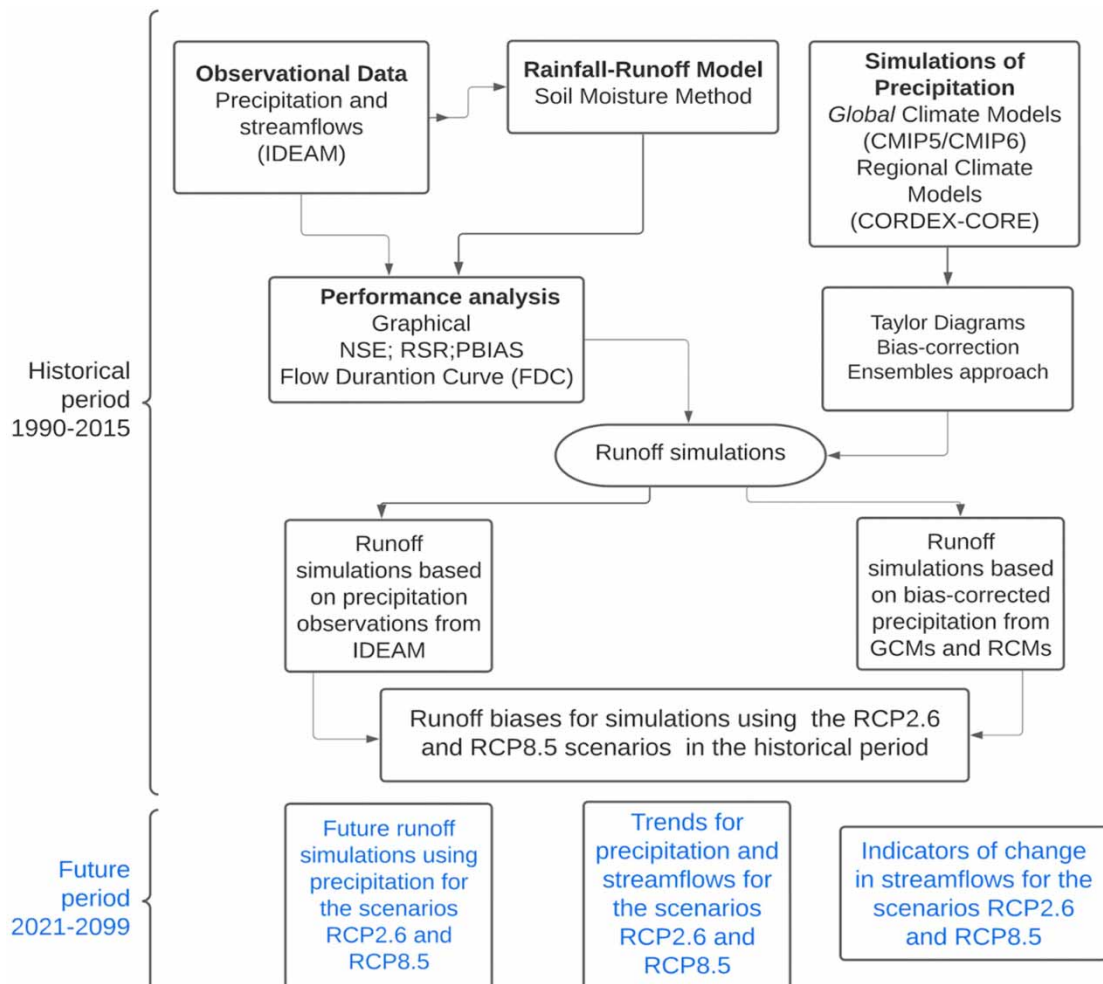


Figure 3 | Methodological flow chart.

Table 2 | Land covers and their percentages on the river basin for each sub-area in the semi-distributed rainfall-runoff model according to the GLCNMO dataset (Kobayashi *et al.* 2017). Values into the square brackets denote the percentage of the area regarding the total area of the river basin

Land Cover	Area (km ²) [%]				Model parameters	
	C1	C2	C3	Sum	RRF (%)	Kc
Broadleaf Forest	23,487.0 [59.4]	18,635.3 [86.7]	74,331.2 [97.4]	116,453.5 [84.8]	8.00	0.75
Shrub	886.2 [2.2]	375.6 [1.7]	375.8 [0.50]	1,637.6 [1.2]	4.00	0.67
Herbaceous	4,249.7 [10.7]	2,122.3 [9.9]	969.4 [1.3]	7,341.5 [5.3]	3.04	0.64
Cropland	10,921.0 [27.6]	358.3 [1.7]	668.5 [0.9]	11,947.7 [8.7]	3.22	0.77
Water bodies	0.9 [0.01]	0.6 [0.0]	0.0 [0.0]	1.5 [0.0]	2.00	0.32
Urban	2.2 [0.0]	0.0 [0.0]	0.0 [0.0]	2.2 [0.0]	1.67	0.44
Total	39,547	21,492	76,345	137,384		

the values of the parameters (Dw , f , Sw , k_s , k_d , z_1 , z_2) while achieving optimization of the simulation performance metrics PBIAS, NSE, and RSR provided by Moriasi *et al.* (2007).

5. RESULTS AND DISCUSSION

5.1. Calibration and validation of the rainfall-runoff model

Figure 4 shows the observed precipitation for the period 1990–2015 (26 years) as well as the observed and simulated streamflow for the same period in the streamflow gauge Guayare. Observations of precipitation (streamflow) show their maximum around 500 mm month⁻¹ (14,000 m³ s⁻¹) and a coherent phasing between the annual cycles of precipitation and streamflow. Hereafter, we are going to illustrate our results and analysis based on the Guayare station (see Figure 1). Figure 4 shows that streamflow simulations for the year 1991 are lower than the observed one, which is related to the first simulated year. In terms of the performance metrics, for the calibration period, the SMM model exhibits PBIAS = 0.07, NSE = 0.70, and RSR = 0.04 while for the validation period, the SMM model exhibits PBIAS = 0.02, NSE = 0.81, and RSR = 0.04. These results indicate that the SMM has a very good performance (Moriasi *et al.* 2007; Le *et al.* 2024; Swilla *et al.* 2024; Wen *et al.* 2024). These

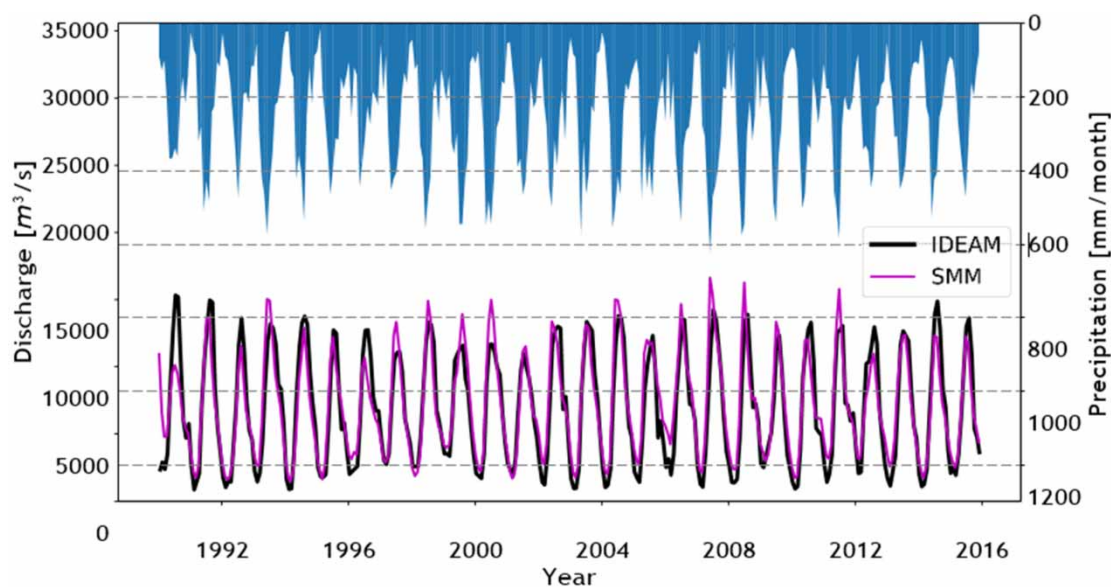


Figure 4 | Precipitation and discharge for the period 1990–2015: (blue) precipitation; (black) observed discharge; (magenta) discharge simulation with the best performance following Moriasi *et al.* (2007).

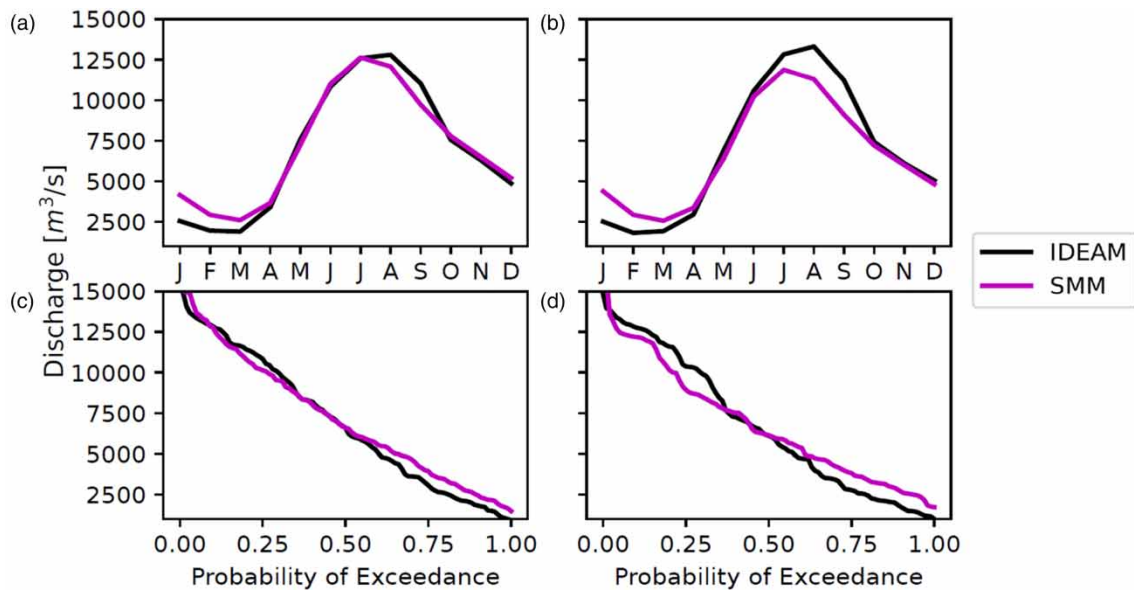


Figure 5 | Annual cycle and flow duration curves for the observed (black) and simulated (magenta) discharges. (a) Annual cycle for the calibration period 1991–2007. (b) Annual cycle for the validation period 2008–2015. (c) Curve of Probability of Exceedance for the calibration period 1991–2007. (d) Curve of Probability of Exceedance for the validation period 2008–2015.

results are found for the value of parameters $Dw = 80$ mm, $f = 0.01$, $Sw = 500$ mm, $k_s = 230$, $k_d = 90.71$ mm, $z_1 = 86.85\%$, $z_2 = 85.77\%$, Albedo = 13%. Moreover, the parameters RRF and k_c are shown in Table 2.

Figures 5(a) and 5(b) show the annual cycles and duration curves for the calibration and validation periods, 1991–2007 and 2008–2015, respectively. This figure indicates that during the dry season (December to March) simulations of streamflow are higher than observations whereas, during the wet season (June to September) simulated streamflow are lower than observations. In addition, Figures 5(c) and (d) confirm that for the calibration period, the simulated discharges with a probability of exceedance of more than 70% are higher than the observations. We find a similar result for the validation period. Furthermore, for discharges with a probability of exceedance lower than 25%, simulations show a better agreement with observations for the calibration period.

In addition, the SMM model performs well in both the calibration and validation phases, effectively capturing the annual cycle variations of observed streamflow as well as its flow duration curve. Although the performance metrics suggest that the SMM model exhibits a slightly lower performance for the calibration period compared to the validation one, the overall results remain satisfactory for the scope of this work (Wen *et al.* 2024).

5.2. Bias correction and ensembles approach

Figure 6 shows the Taylor diagram of precipitation in the upper Orinoco River basin for the period 1990–2015. In general, the climate models exhibit high dispersion in their standard deviations, ranging from 50 to 150 mm month⁻¹. All models show standard deviations below the reference, which can be explained in terms of the difference between time series of observations (an ensemble based on all the IDEAM rain gauges stations within the river basin) and time series from the gridded climate models. Furthermore, the correlation coefficients vary between 0.40 and 0.80, while the centered root-mean-square (RMS) errors range between 100 and 150. The best simulation of monthly precipitation is provided by the regionalization of the NorESM1-M model with RCM REMO, followed by the regionalization of the same model with RegCM4 and the CMIP5 run of the HadGEM2-ES model. Furthermore, all the MPI models (regionalized or not) appear to have the least satisfactory performance in the basin. As a general feature, there is no clear added value from CMIP5 to CMIP6 experiments, the performance of the models is consistent, while RCMs improve the performance of the regionalized GCMs (from CMIP5).

Hence, due to the differences among GCMs and RCMs models, we use the Linear Scaling method (Teutschbein & Seibert 2012; Chathuranika *et al.* 2022) to correct systematic biases in climate models. Furthermore, we compute ensembles for each group of models (CORDEX, CMIP5, and CMIP6) to reduce the uncertainty before the use of these time series for

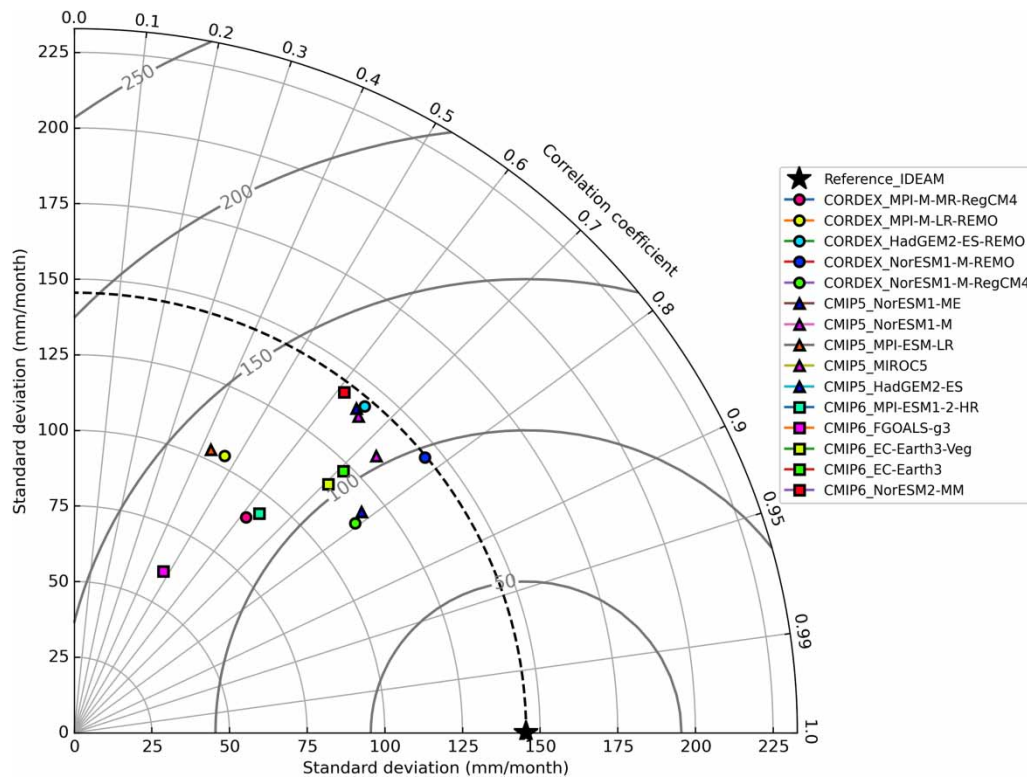


Figure 6 | Taylor diagram for monthly precipitation (without bias correction) in the upper Orinoco River Basin according to CORDEX-CORE (circles), CMIP5 (triangles), and CMIP6 (squares) in the period 1990–2015. Reference (black star) precipitation ensemble from IDEAM rain gauges.

hydrological simulations (Hagedorn *et al.* 2005). Hereafter, we refer to the ensembles for each group of data as Ens_CORDEX for the CORDEX-CORE ensemble, Ens_CMIP5 for the CMIP5 ensemble, Ens_CMIP6 for the CMIP6 ensemble, and Ens_RegIDEAM for the regionalization of the CMIP5 models carried out by IDEAM.

It is important to note that while RCMs and GCMs may not demonstrate high performance according to the metrics of Taylor's diagram, hydrological impact assessments using global and regional projections have been conducted in other regions (Acharki *et al.* 2023; Fang *et al.* 2023; Rudraswamy *et al.* 2023; Salas *et al.* 2023). Furthermore, there is no clear added value from a specific group of global or RCMs (CMIP5, CMIP6, CORDEX-CORE). Therefore, we employ bias correction using the linear scaling method and an ensemble approach to address inconsistencies among simulations, ensuring that the bias-adjusted climate data closely resemble observed climate signals. This facilitates the interpretation of trends and supports further analysis (Semenov & Stratonovitch 2010; Muerth *et al.* 2013; Teng *et al.* 2015; Díaz *et al.* 2021).

5.3. Trends in precipitation and streamflow for different climate change scenarios

We computed the trends in precipitation time series for the future scenarios RCP2.6 and RCP8.5. For the RCP2.6 scenario, all datasets agree with a non-significant decreasing trend of 3.54 mm per decade in the ensemble as shown in Figure 7 (panel a). This result suggests that for this scenario precipitation over the basin would not experience significant changes in the future. In contrast, for the scenario RCP8.5, there is agreement among all datasets with a significant decreasing trend of 23.9 mm per decade in the ensemble as shown in Figure 7 (panel b). These results suggest a reduction of precipitation around ~1.0% (for RCP2.6) and ~6.0% (for RCP8.5) at the end of the century in relation to the long-term mean precipitation over the river basin (~3,100 mm yr⁻¹).

Analogously, we quantified the trends in streamflow time series for both mentioned RCP scenarios as shown in Figure 8. For the scenario RCP2.6, all discharge simulations agree with a non-significant decreasing trend of 1.23 m³ s⁻¹ per year in the ensemble (see Figure 7(a)). This result suggests that for this scenario streamflow of the upper Orinoco River Basin would not

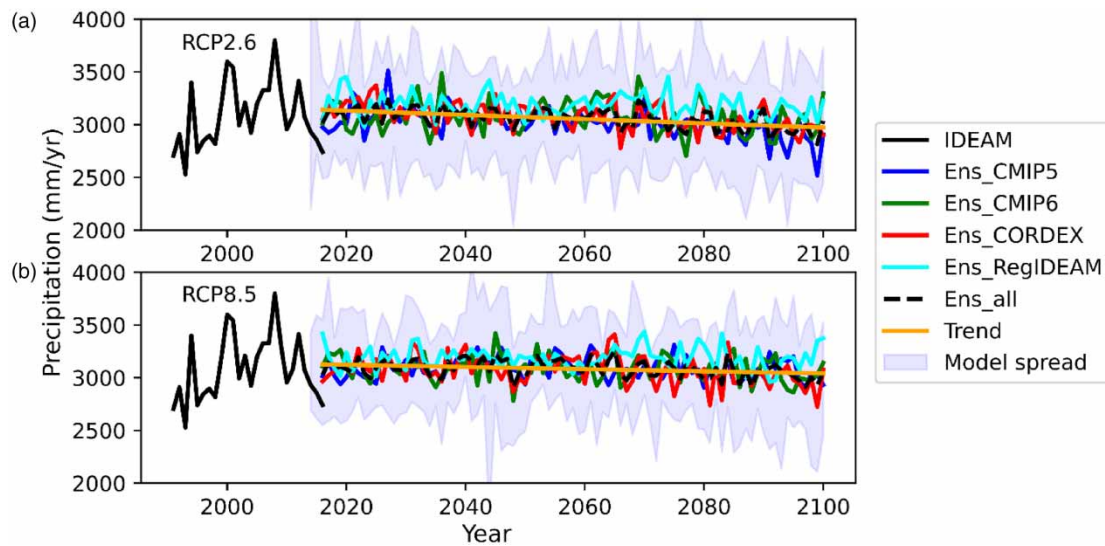


Figure 7 | Future projection of annual precipitation (mm yr^{-1}) in the upper Orinoco River Basin for the period 2020–2099. The trend is drawn for the ensemble of all models. The slope for the RCP2.6, $c = -0.354 \text{ mm yr}^{-1}$, is not significant at the significance level 0.05. The slope for the scenario RCP8.5, $c = -2.386 \text{ mm yr}^{-1}$, is significant at the significance level 0.05. Purple shade represents the intra-ensemble model spread.

experience significant changes in the future. In contrast, for the scenario RCP8.5, there is a significant decreasing trend of $5.97 \text{ m}^3/\text{s}$ per year in the ensemble (see Figure 7(b)). The latter result suggests a reduction of the streamflow around $\sim 1.5\%$ (for RCP2.6) and 7.0% (for RCP8.5) at the end of the century in relation to the long-term mean runoff of the river basin ($\sim 6,200 \text{ m}^3 \text{ s}^{-1}$).

Our findings agree with previous studies indicating changes in streamflow extremes in several South American tropical river basins over the past four decades, characterized by drying trends and accelerated flow rates attributed to factors such as decreasing rainfall, increased agricultural water use, and deforestation (Saurral *et al.* 2017; de Jong *et al.* 2021; Chagas *et al.* 2022). Additionally, the Orinoco River Basin is situated in a region where historical precipitation trends have shown

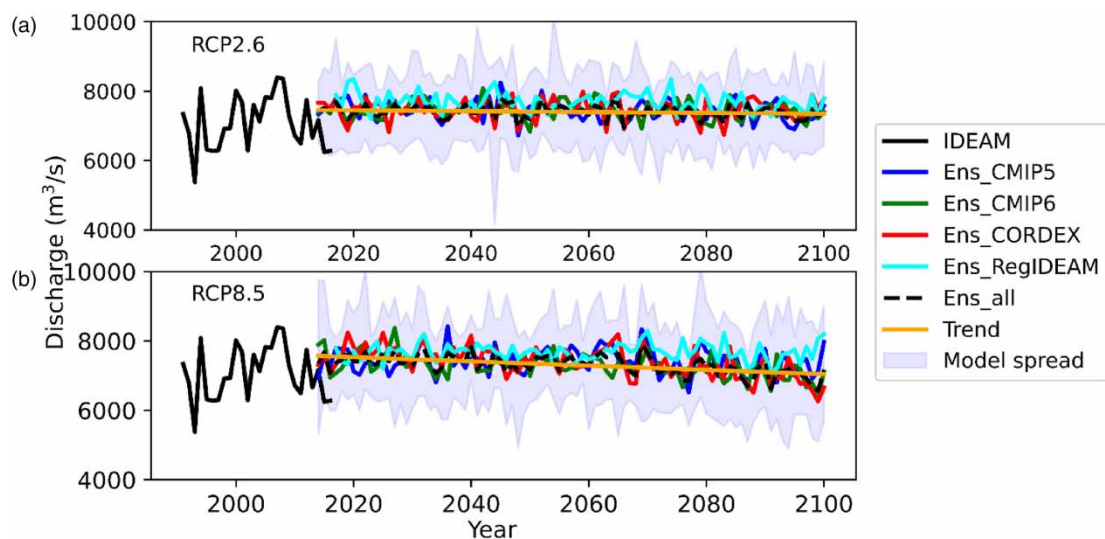


Figure 8 | Future projection of mean annual discharges (m^3/s) in the upper Orinoco River Basin for the period 2020–2099. The trend is drawn for the ensemble of all models. The slope for the scenario RCP2.6 $c = -1.225 \text{ m}^3 \text{ yr}^{-1}$ is not significant at the significance level 0.05. The slope for the scenario RCP8.5 $c = -5.969 \text{ m}^3 \text{ yr}^{-1}$ is significant at the significance level 0.05. Purple shade represents the intra-ensemble model spread.

Table 3 | Indicators of change in the streamflow

RCP	Indicators	2021–2047	2048–2073	2074–2099
RCP2.6	BiasRR	7.19	6.48	4.00
	BiasFMM	7.57	5.03	0.09
	BiasFDCmidslope	−2.61	−2.63	1.28
	BiasFHV	−0.72	−0.31	0.63
	BiasFLV	68.70	18.84	36.37
	DiffQ95	15.31	2.77	5.40
RCP8.5	BiasRR	7.01	6.25	4.08
	BiasFMM	7.62	4.20	−2.66
	BiasFDCmidslope	−3.20	−0.74	2.99
	BiasFHV	−1.74	−0.24	0.65
	BiasFLV	51.26	15.56	25.11
	DiffQ95	17.16	5.92	6.68

a decrease (Carmona & Poveda 2014; Mesa *et al.* 2021; Builes-Jaramillo *et al.* 2024), and projected precipitation decline is robust under the highest emission scenario, both in terms of direction and magnitude (Almazroui *et al.* 2021). Furthermore, our results are consistent with other studies indicating a drier outlook for the Orinoco River Basin throughout the 21st century (Brêda *et al.* 2023; Correa *et al.* 2024).

5.4. Indicators of change in the streamflow

We computed six indicators of runoff change for three periods (2021–2047, 2048–2073, and 2074–2099) and two RCP scenarios (RCP 2.6 and RCP8.5) (see Table 3). Figure 9 shows the FDCs used to compute these change indicators. The percent bias in the mean values (BiasRR) indicates that the mean streamflow for future periods would be higher than observed. These results are analogous for both RCPs decreasing progressively from approximately 7% for 2021–2047 to approximately 4% for 2074–2099. Furthermore, the percent bias in mid-range flow levels (BiasFMM) shows that the BiasFMM of the simulated runoff is higher than the reference for almost all simulated periods with a progressive decrease. In contrast, for the 2074–2099 period and RCP8.5, the BiasFMM shows a reduction in relation to the reference, which suggests that for this scenario the runoff decreases in the mid-range flow levels.

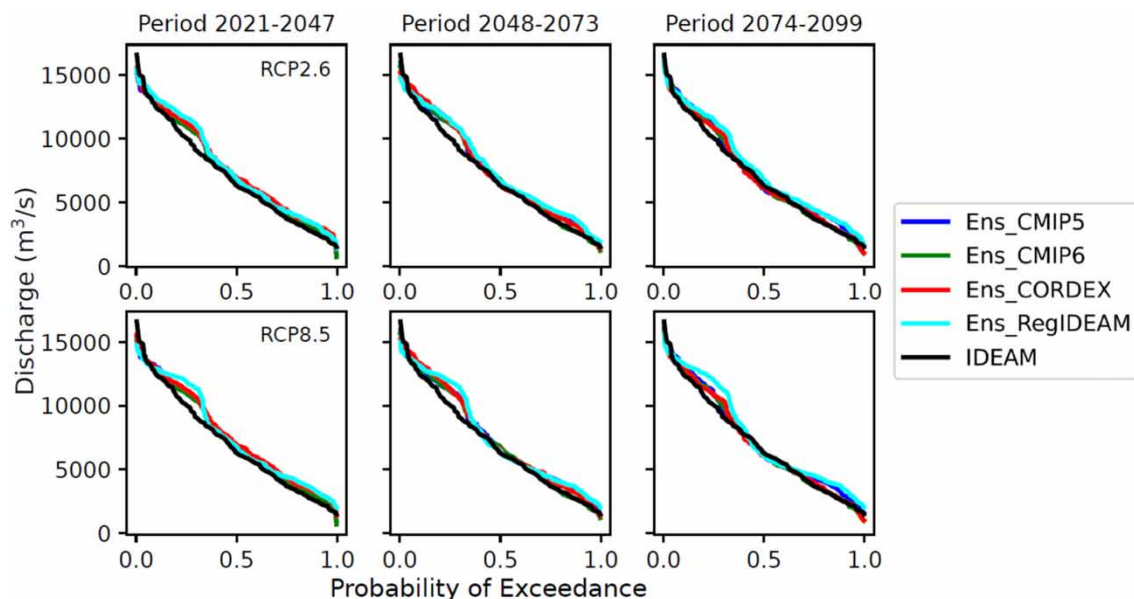


Figure 9 | Exceedance curves for the future simulated streamflow under the scenarios RCP2.6 (upper row) and RCP8.5 (bottom row) for three timelines: 2020s (2021–2047), 2050s (2048–2073), and 2080s (2074–2099).

The percent bias in the slope of the mid-segment of the FDC and the percent bias in the high-segment volumes (BiasFDC-midslope and BiasFHV, respectively) suggest that these indicators are lower for future simulated flows than for the reference ones in the periods 2021–2047 and 2048–2073 for both RCPs, whereas both indices show an increase for the period 2074–2099 for the two RCPs. These results suggest a gradual increase in the mid and high flows in the period 2074–2099. Finally, the differences in long-term baseflow and the differences in the flows at the 95% percentile (BiasFLV and DiffQ95, respectively) agree on an increase in the baseflow for all periods and RCP scenarios.

Previous works have studied the climate change impacts on river discharges through hydrological signatures as a crucial aspect for understanding the overall impact on river systems (Casper *et al.* 2012; Wang *et al.* 2020; Fatehifar *et al.* 2021; Salas *et al.* 2023). For the Orinoco River Basin, although other works have mentioned that climate change has the potential to significantly impact river discharges (Asadieh & Krakauer 2017; Brêda *et al.* 2023), there are no previous works using the signature indices approach proposed by Casper *et al.* (2012). Notwithstanding, other indices for hydrologic alteration have been used to study the characteristics of ecosystems and their maintenance within a basin (Mathews & Richter 2007; Pérez-Sánchez *et al.* 2020; Liu *et al.* 2024). Mathews & Richter (2007) argue that these types of streamflow indices provide information for describing the ways in which an organism experiences river flow variability. In this sense, low flows determine the amount and characteristics (e.g., temperature, flow velocity, connectivity, etc.) of aquatic habitat that is available for most of the year whereas high flows are associated with floods that play a critical role in a river ecosystem (e.g., sediment transport, refresh water quality, remove vegetation, etc.). In this sense, further research is needed in the Orinoco River Basin to improve our understanding about the association between alterations in the streamflow and its biodiversity and ecosystem services (Frappart *et al.* 2014; Lasso *et al.* 2016). Moreover, Pimentel *et al.* (2021) found that agro-industrial expansion and cover land changes in the Orinoco could increase pressure on water resources, leading to critical changes in the water availability regime. Hence, further research is also needed to advance the comprehension of the conjoined effect of those processes and climate change, which is out of the scope of this work.

6. CONCLUSIONS AND FINAL REMARKS

Our results regarding the Upper Orinoco River indicate that precipitation decreases at a rate of 3.54 mm/decade (for RCP2.6) and at a rate of 23.9 mm/decade (for RCP8.5). Hence, these suggest a reduction of precipitation around ~1.0% (for RCP2.6) and ~6.0% (for RCP8.5) at the end of the century in relation to the long-term mean precipitation over the river basin (~3, 100 mm yr⁻¹). Streamflow decreases at a rate of 1.225 m³ yr⁻¹ (for RCP2.6) and decrease at a higher rate of 5.969 m³ yr⁻¹ (for RCP8.5). Hence, these suggest a reduction of streamflow of around 1.5% (for RCP2.6) and 7.0% (for RCP8.5) at the end of the century in relation to the long-term mean runoff of the river basin (~6,200 m³ s⁻¹). All streamflow simulations show a clear difference in the FDCs in the range of 0.2–0.4 which is not observed in the data. This finding in the simulated FDCs may be explained by a systematic bias in the climate models that could not be corrected by the bias correction process. These features require further research if these models are to be used to analyze streamflow in the range of 0.2–0.4 of the FDCs.

Our results show agreement regarding that precipitation and streamflow will decrease according to all datasets, aligning with the conclusions of previous works (Asadieh & Krakauer 2017; Brêda *et al.* 2023; Builes-Jaramillo *et al.* 2024). The predicted reductions for the RCP8.5 scenario in the period 2021–2099 are approximately 190 mm and 477 m³ s⁻¹, respectively. Previous studies have shown that deforestation and agro-industrial expansion in the Colombian Orinoco region may cause reductions in the Guaviare River's low water flows by up to 50% (Pimentel *et al.* 2021). In contrast, our results suggest an increase in low flows associated with climate change of around 7%. The general agreement of the GCMs and RCMs on the trends of simulated streamflow is mostly because the bias correction and ensemble procedures bring simulations closer together.

Our findings show that, for the northern Orinoco, GCMs and RCMs exhibit good simulation of precipitation, with the best performance provided by the CORDEX regionalization of the NorESM1-M. In this sense, our results do not show significant added value from CMIP6 to CMIP5 in terms of simulating precipitation. We hypothesize that this is a region with few observational records, a high mountain range, and a lack of parametrizations for the RCMs and GCMs, which have always been a caveat of climate simulation results in basins like the Amazon and La Plata in South America (Gulizia & Camilloni 2015; Sörensson & Ruscica 2018; Builes-Jaramillo & Pántano 2021).

Further questions about the effect of climate change on precipitation and streamflow of the upper Orinoco River Basin (Guaviare River basin) deserve future work: (i) How are the effects of climate change in conjunction with the land cover

change in the basin?; (ii) How are the changes in low-flow at finer timescales?; (iii) Where in the basin the effects of climate change are more pronounced in the Andean or in the Llanos portion of the river basin?; (iv) How those changes in river flows could affect the river sediment discharge, ecological features, and environmental services?; (v) How to improve the knowledge about sub-surface runoff, interflow, and deep percolation with remote sensing in non-instrumented basins like upper Orinoco River?

ACKNOWLEDGEMENTS

Thanks to IDEAM for precipitation and streamflow data records and the regionalization of the CMIP5 models for Colombia. Thanks to the Stockholm Environment Institute (SEI) for proving a free license to the software Water Evaluation and Planning (WEAP) and particularly to Angelica M. Moncada Aguirre for her technical instruction about WEAP previously to carry out this research. The authors thank the research groups and institutions that provide complete access to the climate model results through the Earth System Grid Federation (ESFG) nodes <https://esgf.llnl.gov/>. Thanks to Prof. Jhony Perez for drawing a schematic representation of the rainfall-runoff model used in this work. Thanks to the Global Land Cover by National Mapping Organizations (GLCNMO) for Land Cover information.

FUNDING

The work of H.D.S. is supported by the Institución Universitaria Colegio Mayor de Antioquia and the Instituto Tecnológico Metropolitano. The work of A.B.-J. is supported by the Institución Universitaria Colegio Mayor de Antioquia. The work by C.F.-V. and J.V. is supported by the project ‘Evaluación de los efectos del cambio climático y de los cambios en las coberturas del suelo y su incorporación en la modelación integral del recurso hídrico: caso de estudio cuenca hidrográfica del Río Gualí’ (Project FAI58). The work by M.B. and Y.T. is supported by the project ‘Modelación de caudales mensuales en la Cuenca del Río Guaviare (Colombia) ante escenarios de cambio climático’ (Project FAI107). The work by K.E. and M.R. is part of SICA, hydroclimatology group (HidroSICA).

AUTHOR CONTRIBUTIONS

H.D.S., A.B.-J., J.V., and C.F.-V. contributed to conceptualization; methodology; formal analysis; investigation; writing – original draft; visualization; writing – review and editing. H.D.S. and A.B.-J. did project administration and supervision. C.F.-V. and J.V. contributed to processing of climate and hydrological data. H.D.S., Y.T., and M.B. did data curation, calibration, and validation of the model, M.R. and K.E. did analysis and processing of land cover.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories: GCMs: ESFG-<https://esgf-node.llnl.gov/projects/esgf-llnl>, Gauges: <https://dhime.ideam.gov.co/>, IDEAM Regionalization: <http://www.ideam.gov.co/web/tiempo-y-clima/escenarios-cambioclimatico>.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

- Acharki, S., Taia, S., Arjdal, Y. & Hack, J. 2023 [Hydrological modeling of spatial and temporal variations in streamflow due to multiple climate change scenarios in northwestern Morocco](https://doi.org/10.1016/j.cliser.2023.100388). *Climate Services* **30**, 100388. <https://doi.org/10.1016/j.cliser.2023.100388>.
- Almazroui, M., Ashfaq, M., Islam, M. N., Rashid, I. U., Kamil, S., Abid, M. A., O'Brien, E., Ismail, M., Reboita, M. S., Sörensson, A. A., Arias, P. A., Alves, L. M., Tippet, M. K., Saeed, S., Haarsma, R., Doblas-Reyes, F. J., Saeed, F., Kucharski, F., Nadeem, I., Silva-Vidal, Y., Rivera, J. A., Ehsan, M. A., Martínez-Castro, D., Muñoz, A. G., Ali, M. A., Coppola, E. & Sylla, M. B. 2021 [Assessment of CMIP6 performance and projected temperature and precipitation changes over South America](https://doi.org/10.1007/s41748-021-00233-6). *Earth Systems and Environment* **5** (2), 155–183. <https://doi.org/10.1007/s41748-021-00233-6>.
- Amanambu, A. C., Li, L., Egbinola, C. N., Obarein, O. A., Mupenzi, C. & Chen, D. 2019 [Spatio-temporal variation in rainfall-runoff erosivity due to climate change in the lower Niger basin, West Africa](https://doi.org/10.1016/j.catena.2018.09.003). *CATENA* **172**, 324–334. <https://doi.org/10.1016/j.catena.2018.09.003>.
- Angarita, H., Wickel, A. J., Sieber, J., Chavarro, J., Maldonado-Ocampo, J. A., Herrera-R., G. A., Delgado, J. & Purkey, D. 2018 [Basin-scale impacts of hydropower development on the mompós depression wetlands, Colombia](https://doi.org/10.5194/hess-22-2839-2018). *Hydrology and Earth System Sciences* **22**, 2839–2865. <https://doi.org/10.5194/hess-22-2839-2018>.

- Arias, P. A., Ortega, G., Villegas, L. D. & Martínez, J. A. 2021 **Colombian climatology in CMIP5/CMIP6 models: Persistent biases and improvements**. *Revista Facultad de Ingeniería Universidad de Antioquia*. <https://doi.org/10.17533/udea.redin.20210525>.
- Asadieh, B. & Krakauer, N. Y. 2017 **Global change in streamflow extremes under climate change over the 21st century**. *Hydrology and Earth System Sciences* **21** (11), 5863–5874. <https://doi.org/10.5194/hess-21-5863-2017>.
- Bellouin, N., Collins, W. J., Culverwell, I. D., Halloran, P. R., Hardiman, S. C., Hinton, T. J., Jones, C. D., McDonald, R. E., McLaren, A. J., O'Connor, F. M., Roberts, M. J., Rodriguez, J. M., Woodward, S., Best, M. J., Brooks, M. E., Brown, A. R., Butchart, N., Dearden, C., Derbyshire, S. H., Dharssi, I., Doutriaux-Boucher, M., Edwards, J. M., Falloon, P. D., Gedney, N., Gray, L. J., Hewitt, H. T., Hobson, M., Huddleston, M. R., Hughes, J., Ineson, S., Ingram, W. J., James, P. M., Johns, T. C., Johnson, C. E., Jones, A., Jones, C. P., Joshi, M. M., Keen, A. B., Liddicoat, S., Lock, A. P., Maidens, A. V., Manners, J. C., Milton, S. F., Rae, J. G. L., Ridley, J. K., Sellar, A., Senior, C. A., Totterdell, I. J., Verhoef, A., Vidale, P. L. & Wiltshire, A. 2011 **The HadGEM2 family of met office unified model climate configurations**. *Geoscientific Model Development* **4** (3), 723–757. <https://doi.org/10.5194/gmd-4-723-2011>.
- Bentsen, M., Bethke, I., Debernard, J.B., Iversen, T., Kirkevåg, A., Seland, Ø., Drange, H., Roelandt, C., Seierstad, I. A., Hoose, C. & Kristjánsson, J. E. 2013 **The Norwegian earth system model, NorESM1-M – part 1: Description and basic evaluation of the physical climate**. *Geoscientific Model Development* **6** (3), 687–720. <https://doi.org/10.5194/gmd-6-687-2013>.
- Brêda, J. P. L. F., de Paiva, R. C. D., Chou, S. C. & Collischonn, W. 2022 **Assessing extreme precipitation from a regional climate model in different spatial–temporal scales: A hydrological perspective in South America**. *International Journal of Climatology*. <https://doi.org/10.1002/joc.7782>.
- Brêda, J. P. L. F., Cauduro Dias de Paiva, R., Siqueira, V. A. & Collischonn, W. 2023 **Assessing climate change impact on flood discharge in South America and the influence of its main drivers**. *Journal of Hydrology* **619**, 129284. <https://doi.org/10.1016/j.jhydrol.2023.129284>.
- Builes-Jaramillo, A. & Pántano, V. 2021 **Comparison of spatial and temporal performance of two Regional Climate Models in the Amazon and La Plata river basins**. *Atmospheric Research* **250**. <https://doi.org/10.1016/j.atmosres.2020.105413>.
- Builes-Jaramillo, A., Salas, H. D., Valencia, J. & Florian, C. 2024 **Orinoco Revisited: Comprehensive analysis of the Orinoco River Basin Present and Future Hydroclimate**. *Atmósfera*, in press.
- Carmona, A. M. & Poveda, G. 2014 **Detection of long-term trends in monthly hydro-climatic series of Colombia through Empirical Mode Decomposition**. *Climatic Change* **123** (2), 301–313. <https://doi.org/10.1007/s10584-013-1046-3>.
- Carvalho, V. S. O., Alvarenga, L. A., Melo, P. A., Tomasella, J., Mello, C. R. de & Martins, M. A. 2022 **Climate change impact assessment in a tropical headwater basin**. *Ambiente e Água An Interdisciplinary Journal of Applied Science* **17** (1), 1–19. <https://doi.org/10.4136/ambi-agua.2753>.
- Casper, M. C., Grigoryan, G., Gronz, O., Gutjahr, O., Heinemann, G., Ley, R. & Rock, A. 2012 **Analysis of projected hydrological behavior of catchments based on signature indices**. *Hydrology and Earth System Sciences* **16** (2), 409–421. <https://doi.org/10.5194/hess-16-409-2012>.
- Chagas, V. B. P., Chaffe, P. L. B. & Blöschl, G. 2022 **Climate and land management accelerate the Brazilian water cycle**. *Nature Communications* **13** (1), 5136. <https://doi.org/10.1038/s41467-022-32580-x>.
- Chathuranika, I. M., Gunathilake, M. B., Azamathulla, H. Md. & Rathnayake, U. 2022 **Evaluation of future streamflow in the upper part of the Nilwala River Basin (Sri Lanka) under climate change**. *Hydrology* **9** (3), 48. <https://doi.org/10.3390/hydrology9030048>.
- Chawla, I. & Mujumdar, P. P. 2015 **Isolating the impacts of land use and climate change on streamflow**. *Hydrology and Earth System Sciences* **19** (8), 3633–3651. <https://doi.org/10.5194/hess-19-3633-2015>.
- Christensen, J. H., Boberg, F., Christensen, O. B. & Lucas-Picher, P. 2008 **On the need for bias correction of regional climate change projections of temperature and precipitation**. *Geophysical Research Letters* **35** (L20), 709. <https://doi.org/10.1029/2008GL035694>.
- Chu, H., Wei, J., Qiu, J., Li, Q. & Wang, G. 2019 **Identification of the impact of climate change and human activities on rainfall-runoff relationship variation in the three-river headwaters region**. *Ecological Indicators* **106**, 105,516. <https://doi.org/10.1016/j.ecolind.2019.105516>.
- Ciarlo, J. M., Coppola, E., Fantini, A., Giorgi, F., Gao, X., Tong, Y., Glazer, R. H., Torres Alavez, J. A., Sines, T., Pichelli, E., Raffaele, F., Das, S., Bukovsky, M., Ashfaq, M., Im, E.-S., Nguyen-Xuan, T., Teichmann, C., Remedio, A., Remke, T., Bülow, K., Weber, T., Buntmeyer, L., Sieck, K., Rechid, D. & Jacob, D. 2021 **A new spatially distributed added value index for regional climate models: The EURO-CORDEX and the CORDEX-CORE highest resolution ensembles**. *Climate Dynamics* **57** (5–6), 1403–1424. <https://doi.org/10.1007/s00382-020-05400-5>.
- Clerici, N., Armenteras, D., Kareiva, P., Botero, R., Ramírez-Delgado, J. P., Forero-Medina, G., Ochoa, J., Pedraza, C., Schneider, L., Lora, C., Gómez, C., Linares, M., Hirashiki, C. & Biggs, D. 2020 **Deforestation in Colombian protected areas increased during post-conflict periods**. *Scientific Reports* **10** (1), 1–10. <https://doi.org/10.1038/s41598-020-61861-y>.
- Correa, I. C., Arias, P. A., Vieira, S. C. & Martínez, J. A. 2024 **A drier Orinoco basin during the twenty-first century: The role of the Orinoco low-level jet**. *Climate Dynamics* **62** (3), 2369–2398. <https://doi.org/10.1007/s00382-023-07028-7>.
- de Jong, P., Barreto, T. B., Tanajura, C. A. S., Oliveira-Esquerre, K. P., Kiperstok, A. & Andrade Torres, E. 2021 **The impact of regional climate change on hydroelectric resources in South America**. *Renewable Energy* **173**, 76–91. <https://doi.org/10.1016/j.renene.2021.03.077>.
- De Los Rios, C. 2022 **The double fence: overlapping institutions and deforestation in the Colombian Amazon**. *Ecological Economics* **193**, 107,274. <https://doi.org/10.1016/j.jecolecon.2021.107274>.
- Döscher, R., Acosta, M., Alessandri, A., Anthoni, P., Arsouze, T., Bergman, T., Bernardello, R., Boussetta, S., Caron, L.-P., Carver, G., Castrillo, M., Catalano, F., Cvijanovic, I., Davini, P., Dekker, E., Doblas-Reyes, F. J., Docquier, D., Echevarria, P., Fladrich, U., Fuentes-Franco, R., Gröger, M., v. Hardenberg, J., Hieronymus, J., Karami, M. P., Keskinen, J.-P., Koenigk, T., Makkonen, R., Massonnet, F.,

- Ménégoz, M., Miller, P. A., Moreno-Chamarro, E., Nieradzik, L., van Noije, T., Nolan, P., O'Donnell, D., Ollinaho, P., van den Oord, G., Ortega, P., Prims, O. T., Ramos, A., Reerink, T., Rousset, C., Ruprich-Robert, Y., Le Sager, P., Schmith, T., Schrödner, R., Serva, F., Sicardi, V., Sloth Madsen, M., Smith, B., Tian, T., Tourigny, E., Uotila, P., Vancoppenolle, M., Wang, S., Wårlind, D., Willén, U., Wyser, K., Yang, S., Yepes-Arbós, X. & Zhang, Q. 2022 *The EC-earth3 earth system model for the coupled model intercomparison project 6. Geoscientific Model Development* **15** (7), 2973–3020. <https://doi.org/10.5194/gmd-15-2973-2022>.
- Díaz, L. B., Saurral, R. I. & Vera, C. S. 2021 *Assessment of South America summer rainfall climatology and trends in a set of global climate models large ensembles. International Journal of Climatology* **41**. <https://doi.org/10.1002/joc.6643>.
- Edwards, P. N. 2011 *History of climate modeling. WIREs Climate Change* **2** (1), 128–139. <https://doi.org/10.1002/wcc.95>, <https://onlinelibrary.wiley.com/doi/10.1002/wcc.95>
- Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J. & Taylor, K. E. 2016 *Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization. Geoscientific Model Development* **9** (5), 1937–1958. <https://doi.org/10.5194/gmd-9-1937-2016>.
- Falco, M., Carril, A. F., Menéndez, C. G., Zaninelli, P. G. & Li, L. Z. X. 2019 *Assessment of CORDEX simulations over South America: Added value on seasonal climatology and resolution considerations. Climate Dynamics* **52** (7-8), 4771–4786. <https://doi.org/10.1007/s00382-018-4412-z>.
- Fang, G., Li, Z., Chen, Y., Liang, W., Zhang, X. & Zhang, Q. 2023 *Projecting the impact of climate change on runoff in the Tarim river simulated by the soil and water assessment tool glacier model. Remote Sensing* **15** (16), 3922. <https://doi.org/10.3390/rs15163922>.
- Fatehifar, A., Goodarzi, M. R., Montazeri Hedesh, S. S. & Siahvashi Dastjerdi, P. 2021 *Assessing watershed hydrological response to climate change based on signature indices. Journal of Water and Climate Change* **12** (6), 2579–2593. <https://doi.org/10.2166/wcc.2021.293>.
- Foley, A. 2010 *Uncertainty in regional climate modelling: A review. Progress in Physical Geography: Earth and Environment* **34** (5), 647–670. <https://doi.org/10.1177/0309133310375654>.
- Frappart, F., Papa, F., Malbeteau, Y., León, J., Ramillien, G., Prigent, C., Seoane, L., Seyler, F. & Calmant, S. 2012 *Surface freshwater storage and dynamics in the Amazon basin during the 2005 exceptional drought. Environmental Research Letters* **7** (4), 044,010. <https://doi.org/10.1088/1748-9326/7/4/044010>.
- Frappart, F., Papa, F., Santos da Silva, J., Ramillien, G., Prigent, C., Seyler, F. & Calmant, S. 2014 *Surface freshwater storage variations in the Orinoco floodplains using multi-Satellite observations. Remote Sensing* **7** (1), 89–110. <https://doi.org/10.3390/rs70100089>.
- Ganzenmüller, R., Sylvester, J. M. & Castro-Nunez, A. 2022 *What peace means for deforestation: an analysis of local deforestation dynamics in times of conflict and peace in Colombia. Frontiers in Environmental Science* **10**. <https://doi.org/10.3389/fenvs.2022.803368>.
- Giorgi, F. 2019 *Thirty years of regional climate modeling: Where are we and where are we going next? Journal of Geophysical Research: Atmospheres* 2018JD030094. <https://doi.org/10.1029/2018JD030094>.
- Giorgi, F., Coppola, E., Teichmann, C. & Jacob, D. 2021 *Editorial for the CORDEX-CORE experiment I special issue. Climate Dynamics* **57** (5–6), 1265–1268. <https://doi.org/10.1007/s00382-021-05902-w>.
- Gulizia, C. & Camilloni, I. 2015 *Comparative analysis of the ability of a set of CMIP3 and CMIP5 global climate models to represent precipitation in South America. International Journal of Climatology* **35** (4), 583–595. <https://doi.org/10.1002/joc.4005>.
- Gutjahr, O., Putrasahan, D., Lohmann, K., Jungclaus, J. H., von Storch, J.-S., Brüggemann, N., Haak, H. & Stössel, A. 2019 *Max Planck institute earth system model (MPI-ESM1.2) for the high-resolution model intercomparison project (HighResMIP). Geoscientific Model Development* **12** (7), 3241–3281. <https://doi.org/10.5194/gmd-12-3241-2019>.
- Hagedorn, R., Doblas-Reyes, F. J. & Palmer, T. N. 2005 *The rationale behind the success of multi-model ensembles in seasonal forecasting – I. Basic concept. Tellus A* **57** (3), 219–233. <https://doi.org/10.1111/j.1600-0870.2005.00103.x>.
- Hawkins, E. & Sutton, R. 2009 *The potential to narrow uncertainty in regional climate predictions. Bulletin of the American Meteorological Society* **90** (8), 1095–1108. <https://doi.org/10.1175/2009BAMS2607.1>.
- IPCC. 2022 *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/ar6-syr/*
- Jiang, T., Chen, Y. D., Xu, C., Chen, Xiaohong, Chen, Xi & Singh, V. P. 2007 *Comparison of hydrological impacts of climate change simulated by six hydrological models in the Dongjiang Basin, South China. Journal of Hydrology* **336** (3-4), 316–333. <https://doi.org/10.1016/j.jhydrol.2007.01.010>.
- Jones, C. D., Hughes, J. K., Bellouin, N., Hardiman, S.C., Jones, G. S., Knight, J., Liddicoat, S., O'Connor, F. M., Andres, R. J., Bell, C., Boo, K.-O., Bozzo, A., Butchart, N., Cadule, P., Corbin, K. D., Doutriaux-Boucher, M., Friedlingstein, P., Gornall, J., Gray, L., Halloran, P. R., Hurtt, G., Ingram, W. J., Lamarque, J.-F., Law, R. M., Meinshausen, M., Osprey, S., Palin, E. J., Parsons Chini, L., Raddatz, T., Sanderson, M. G., Sellar, A. A., Schurer, A., Valdes, P., Wood, N., Woodward, S., Yoshioka, M. & Zerroukat, M. 2011 *The HadGEM2-ES implementation of CMIP5 centennial simulations. Geoscientific Model Development* **4** (3), 543–570. <https://doi.org/10.5194/gmd-4-543-2011>.
- Jungclaus, J.H., Fischer, N., Haak, H., Lohmann, K., Marotzke, J., Matei, D., Mikolajewicz, U., Notz, D. & Storch, J. S. 2013 *Characteristics of the ocean simulations in the Max Planck Institute Ocean Model (MPIOM) the ocean component of the MPI-Earth system model. Journal of Advances in Modeling Earth Systems* **5** (2), 422–446. <https://doi.org/10.1002/jame.20023>.
- Kendall, M. 1975 *Rank Correlation Methods* (4th edn). Charles Griffin, London. [https://www.scirp.org/\(S\(351jmbntvnsjt1aadkposzje\)\)/reference/ReferencesPapers.aspx?ReferenceID=2099295](https://www.scirp.org/(S(351jmbntvnsjt1aadkposzje))/reference/ReferencesPapers.aspx?ReferenceID=2099295)

- Kobayashi, T., Tateishi, R., Alsaadeh, B., Sharma, R. C., Wakaizumi, T., Miyamoto, D., Bai, X., Long, B. D., Gegentana, G., Maitiniyazi, A., Cahyana, D., Hairati, A., Morifuji, Y., Abake, G., Pratama, R., Zhang, N., Alifu, Z., Shirahata, T., Mi, L., Iizuka, K., Yusupuijiang, A., Rinawan, F. R., Bhattarai, R. & Phong, D. X. 2017 Production of global land cover data – GLCNMO2013. *Journal of Geography and Geology* **9** (3), 1. <https://doi.org/10.5539/jgg.v9n3p1>.
- Lasso, C. A., Machado-Allison, A. & Taphorn, D. C. 2016 Fishes and aquatic habitats of the Orinoco River Basin: Diversity and conservation. *Journal of Fish Biology* **89** (1), 174–191. <https://doi.org/10.1111/jfb.13010>.
- Le, X.-H., Kim, Y., van Binh, D., Jung, S., Hai Nguyen, D. & Lee, G. 2024 Improving rainfall-runoff modeling in the Mekong river basin using bias-corrected satellite precipitation products by convolutional neural networks. *Journal of Hydrology* **630**, 130762. <https://doi.org/10.1016/j.jhydrol.2024.130762>.
- Lee, M., Im, E. & Bae, D. 2019 Impact of the spatial variability of daily precipitation on hydrological projections: A comparison of GCM- and RCM-driven cases in the Han River basin, Korea. *Hydrological Processes* <https://doi.org/10.1002/hyp.13469>.
- Li, L., Yu, Y., Tang, Y., Lin, P., Xie, J., Song, M., Dong, L., Zhou, T., Liu, L., Wang, Lu, Pu, Y., Chen, X., Chen, L., Xie, Z., Liu, Hongbo, Zhang, L., Huang, X., Feng, T., Zheng, W., Xia, K., Liu, Hailong, Liu, J., Wang, Y., Wang, Longhuan, Jia, B., Xie, F., Wang, B., Zhao, S., Yu, Z., Zhao, B. & Wei, J. 2020 The flexible global ocean-atmosphere-land system model grid-point version 3 (FGOALS-g3): Description and evaluation. *Journal of Advances in Modeling Earth Systems* **12** (9). <https://doi.org/10.1029/2019MS002012>.
- Liu, Y., Liu, F., Chen, C., Chen, Q., Zhang, J., Mo, K., Jiang, Q. & Yao, S. 2024 A holistic approach to projecting streamflow and analyzing changes in ecologically relevant hydrological indicators under climate and land use/cover change. *Journal of Hydrology* **632**, 130863. <https://doi.org/10.1016/j.jhydrol.2024.130863>.
- Llopart, M., Simoes Reboita, M. & Porfirio da Rocha, R. 2020 Assessment of multi-model climate projections of water resources over South America CORDEX domain. *Climate Dynamics* **54** (1–2), 99–116. <https://doi.org/10.1007/s00382-019-04990-z>.
- López, R., Del Castillo, C. E., Miller, R. L., Salisbury, J. & Wissler, D. 2012 Examining organic carbon transport by the Orinoco River using SeaWiFS imagery. *Journal of Geophysical Research: Biogeosciences* **117** (3), 1–13. <https://doi.org/10.1029/2012JG001986>.
- Mathews, R. & Richter, B. D. 2007 Application of the indicators of hydrologic alteration software in environmental flow setting 1. *JAWRA Journal of the American Water Resources Association* **43** (6), 1400–1413. <https://doi.org/10.1111/j.1752-1688.2007.00099.x>.
- Meade, R. H. 2008 Transcontinental moving and storage: The Orinoco and Amazon rivers transfer the Andes to the atlantic. *Large Rivers: Geomorphology and Management* 45–63. <https://doi.org/10.1002/9780470723722.ch4>.
- Mesa, O., Urrea, V. & Ochoa, A. 2021 Trends of hydroclimatic intensity in Colombia. *Climate* **9** (7), 120. <https://doi.org/10.3390/cli9070120>.
- Mora, A., Moreau, C., Moquet, J.-S., Gallay, M., Mahlke, J. & Laraque, A. 2020 Hydrological control, fractionation, and fluxes of dissolved rare earth elements in the lower Orinoco River, Venezuela. *Applied Geochemistry* **112**. <https://doi.org/10.1016/j.apgeochem.2019.104462>.
- Moradkhani, H. & Sorooshian, S. 2009 General review of rainfall-runoff modeling: model calibration, data assimilation, and uncertainty analysis. In: *Hydrological Modelling and the Water Cycle* (Sorooshian, S., Hsu, K.-L., Coppola, E., Tomassetti, B., Verdecchia, M., Visconti, G., eds.). Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 1–24. <https://doi.org/10.1007/978-3-540-77843-1>.
- Moriasi, D. N., Arnold, J. G. & Van Liew, M. W. 2007 Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE* **50** (3), 885–900. <https://doi.org/10.13031/2013.23153>.
- Muerth, M. J., Gauvin St-Denis, B., Ricard, S., Velázquez, J. A., Schmid, J., Minville, M., Caya, D., Chaumont, D., Ludwig, R. & Turcotte, R. 2013 On the need for bias correction in regional climate scenarios to assess climate change impacts on river runoff. *Hydrology and Earth System Sciences* **17**, 1189–1204. <https://doi.org/10.5194/hess-17-1189-2013>.
- Pérez-Sánchez, J., Senent-Aparicio, J., Martínez Santa-María, C. & López-Ballesteros, A. 2020 Assessment of ecological and hydro-geomorphological alterations under climate change using SWAT and IAHRIS in the Eo river in northern Spain. *Water* **12** (6), 1745. <https://doi.org/10.3390/w12061745>.
- Perreault, L., Haché, M., Slivitzky, M. & Bobée, B. 1999 Detection of changes in precipitation and runoff over eastern Canada and U.S. using a Bayesian approach. *Stochastic Environmental Research and Risk Assessment (SERRA)* **13** (3), 201–216. <https://doi.org/10.1007/s004770050039>.
- Pimentel, J. N., Rogéiz Prada, C. A. & Walschburger, T. 2021 Hydrological modeling for multifunctional landscape planning in the Orinoquia Region of Colombia. *Frontiers in Environmental Science* **9**. <https://doi.org/10.3389/fenvs.2021.673215>.
- Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L. A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Streffer, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J. C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A. & Tavoni, M. 2017 The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* **42**, 153–168.
- Rodríguez-de-Francisco, J. C., del Cairo, C., Ortiz-Gallego, D., Velez-Triana, J. S., Vergara-Gutiérrez, T. & Hein, J. 2021 Post-conflict transition and REDD+ in Colombia: Challenges to reducing deforestation in the Amazon. *Forest Policy and Economics* **127**. <https://doi.org/10.1016/j.forpol.2021.102450>.
- Rudraswamy, G. K., Manikanta, V. & Umamahesh, N. 2023 Hydrological assessment of the Tungabhadra River Basin based on CMIP6 GCMs and multiple hydrological models. *Journal of Water and Climate Change* **14** (5), 1371–1394. <https://doi.org/10.2166/wcc.2023.272>.

- Salas, H. D., Florian, C., Builes-Jaramillo, A., Valencia, J., Mena, D., Parra, J. C. & Valdel, J. C. 2023 *Climate change and its effects on the streamflow of an Andean river basin with volcanic activity*. *Journal of Water and Climate Change* jwc2023340. <https://doi.org/10.2166/wcc.2023.340>.
- Saurral, R. I., Camilloni, I. A. & Barros, V. R. 2017 *Low-frequency variability and trends in centennial precipitation stations in southern South America*. *International Journal of Climatology* **37** (4), 1774–1793. <https://doi.org/10.1002/joc.4810>.
- Seland, Ø., Bentsen, M., Olivié, D., Toniazzo, T., Gjermundsen, A., Graff, L. S., Debernard, J. B., Gupta, A.K., He, Y.-C., Kirkevåg, A., Schwinger, J., Tjiputra, J., Aas, K. S., Bethke, I., Fan, Y., Griesfeller, J., Grini, A., Guo, C., Ilicak, M., Karset, I. H. H., Landgren, O., Liakka, J., Moseid, K. O., Nummelin, A., Spensberger, C., Tang, H., Zhang, Z., Heinze, C., Iversen, T. & Schulz, M. 2020 *Overview of the Norwegian Earth System Model (NorESM2) and key climate response of CMIP6 DECK, historical, and scenario simulations*. *Geoscientific Model Development* **13** (12), 6165–6200. <https://doi.org/10.5194/gmd-13-6165-2020>.
- Semenov, M. & Stratonovitch, P. 2010 *Use of multi-model ensembles from global climate models for assessment of climate change impacts*. *Climate Research* **41**, 1–14. <https://doi.org/10.3354/cr00836>.
- Sen, P. 1968 *Estimates of the regression coefficient based on Kendall's tau*. *Journal of the American Statistical Association* **63** (324), 1379–1389.
- Silva León, G. 2005 *La cuenca del río Orinoco: Visión hidrográfica y balance hídrico*. *Revista Geográfica Venezolana* **46** (1), 75–108.
- Sörensson, A. A. & Ruscica, R. C. 2018 *Intercomparison and uncertainty assessment of nine evapotranspiration estimates over South America*. *Water Resources Research* **54** (4), 2891–2908. <https://doi.org/10.1002/2017WR021682>.
- Swilla, L., Katambara, Z. & Lingwanda, M. 2024 *Calibration and verification of a hydrological SWMM model for the ungauged Kinyerezi River catchment in Dar es Salaam, Tanzania*. *Modeling Earth Systems and Environment* **10** (2), 2803–2818. <https://doi.org/10.1007/s40808-023-01929-6>.
- Taylor, K. E., Stouffer, R. J. & Meehl, G. A. 2012 *An overview of CMIP5 and the experiment design*. *Bulletin of the American Meteorological Society* **93** (4), 485–498. <https://doi.org/10.1175/BAMS-D-11-00094.1>.
- Teng, J., Potter, N. J., Chiew, F. H. S., Zhang, L., Wang, B., Vaze, J. & Evans, J. P. 2015 *How does bias correction of regional climate model precipitation affect modelled runoff?* *Hydrology and Earth System Sciences* **19** (2), 711–728. <https://doi.org/10.5194/hess-19-711-2015>.
- Teutschbein, C. & Seibert, J. 2012 *Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods*. *Journal of Hydrology* **456–457**, 12–29. <https://doi.org/10.1016/j.jhydrol.2012.05.052>.
- Tjiputra, J. F., Roelandt, C., Bentsen, M., Lawrence, D. M., Lorentzen, T., Schwinger, J., Seland, Ø. & Heinze, C. 2013 *Evaluation of the carbon cycle components in the Norwegian Earth System Model (NorESM)*. *Geoscientific Model Development* **6** (2), 301–325. <https://doi.org/10.5194/gmd-6-301-2013>.
- Villarini, G., Serinaldi, F., Smith, J. A. & Krajewski, W. F. 2009 *On the stationarity of annual flood peaks in the continental United States during the 20th century*. *Water Resources Research* **45** (8). <https://doi.org/10.1029/2008WR007645>.
- Wang, W., Zhang, Y. & Tang, Q. 2020 *Impact assessment of climate change and human activities on streamflow signatures in the Yellow River Basin using the Budyko hypothesis and derived differential equation*. *Journal of Hydrology* **591**, 125460. <https://doi.org/10.1016/j.jhydrol.2020.125460>.
- Warne, A. G., Meade, R. H. & White, W. A. 2002 *Regional controls on geomorphology, hydrology, and ecosystem integrity in the Orinoco delta, Venezuela*. *Geomorphology* **44** (3–4), 273–307.
- Watanabe, M., Suzuki, T., Oishi, R., Komuro, Y., Watanabe, S., Emori, S., Takemura, T., Chikira, M., Ogura, T., Sekiguchi, M., Takata, K., Yamazaki, D., Yokohata, T., Nozawa, T., Hasumi, H., Tatebe, H. & Kimoto, M. 2010 *Improved climate simulation by MIROC5: Mean states, variability, and climate sensitivity*. *Journal of Climate* **23** (23), 6312–6335. <https://doi.org/10.1175/2010JCLI3679.1>.
- Wen, S., Su, B., Huang, J., Wang, Y., Treu, S., Jiang, F., Jiang, S. & Jiang, H. 2024 *Attribution of streamflow changes during 1961–2019 in the Upper Yangtze and the Upper Yellow River basins*. *Climatic Change* **177** (4), 60. <https://doi.org/10.1007/s10584-024-03712-7>.
- Yates, D., Sieber, J., Purkey, D. & Huber-Lee, A. 2005 *WEAP21—A demand-, priority-, and preference-driven water planning model*. *Water International* **30** (4), 487–500. <https://doi.org/10.1080/02508060508691893>.
- Zamudio, J. E. & Maldonado-ocampo, J. A. 2022 *Prioridades para la conservación de los peces de agua dulce en la Orinoquia andina de Colombia*. *Caldasia* **44** (1), 41–53.
- Zanchettin, D., Rubino, A., Matei, D., Bothe, O. & Jungclaus, J. H. 2013 *Multidecadal-to-centennial SST variability in the MPI-ESM simulation ensemble for the last millennium*. *Climate Dynamics* **40** (5–6), 1301–1318. <https://doi.org/10.1007/s00382-012-1361-9>.
- Zeng, F., Ma, M.-G., Di, D.-R. & Shi, W.-Y. 2020 *Separating the impacts of climate change and human activities on runoff: A review of method and application*. *Water* **12** (8), 2201. <https://doi.org/10.3390/w12082201>.
- Zhang, Y. K. & Schilling, K. 2006 *Increasing streamflow and baseflow in Mississippi River since the 1940s: Effect of land use change*. *Journal of Hydrology* **324** (1–4), 412–422. <https://doi.org/10.1016/j.jhydrol.2005.09.033>.
- Zhang, Z., Duan, K., Liu, H., Meng, Y., Chen, R., Li, D. & Li, S. 2012 *Pre-industrial and mid-Pliocene simulations with NorESM-L*. *Geoscientific Model Development* **5** (2), 523–533. <https://doi.org/10.5194/gmd-5-523-2012>.
- Zhang, Z. S., Nisancioglu, K., Bentsen, M., Tjiputra, J., Bethke, I., Yan, Q., Risebrobakken, B., Andersson, C. & Jansen, E. 2022 *Runoff projections of the Qinling Mountains and their impact on water demand of Guanzhong region in Northwest China*. *Journal of Mountain Science*. <https://doi.org/10.1007/s11629-022-7358-x>.

LISTADO REVISTAS HOMOLOGADAS

Código: M601PR03F01

Versión: 00

Fecha: 2020-07-08

Página: 1 de 1

No.	NOMBRE	ISSN	CATEGORIA	VIGENCIA	LISTA_SIR
14544	RIME RIVISTA DELL ISTITUTO DI STORIA DELL EUROPA MEDITERRANEA	2035-794X	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR
14545	NEUROLOGY INTERNATIONAL	2035-8377; 2035-8385	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR; Journal Citation Reports - JCR
14546	VALORI E VALUTAZIONI	2036-2404	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR
14547	EUROPEAN JOURNAL OF PRAGMATISM AND AMERICAN PHILOSOPHY	2036-4091	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR; Journal Citation Reports - JCR
14548	DERMATOLOGY REPORTS	2036-7392; 2036-7406	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR; Journal Citation Reports - JCR
14549	INFECTIOUS DISEASE REPORTS	2036-7430; 2036-7449	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR; Journal Citation Reports - JCR
14550	PEDIATRIC REPORTS	2036-749X; 2036-7503	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR; Journal Citation Reports - JCR
14551	INTERNATIONAL JOURNAL OF PLANT BIOLOGY	2037-0156; 2037-0164	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR
14552	ENTHYMEMA	2037-2426	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR; Journal Citation Reports - JCR
14553	PSL QUARTERLY REVIEW	2037-3635; 2037-3643	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR; Journal Citation Reports - JCR
14554	JLIS IT	2038-1026; 2038-5366	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR
14555	ARCHIVIO ANTROPOLOGICO MEDITERRANEO	2038-3215	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR
14556	CAPITALE CULTURALE	2039-2362	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR
14557	RIVISTA INTERNAZIONALE DI FILOSOFIA E PSICOLOGIA	2039-4667; 2239-2629	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR; Journal Citation Reports - JCR
14558	INTERNATIONAL JOURNAL ON COMMUNICATIONS ANTENNA AND PROPAGATION	2039-5086; 2533-2929	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR
14559	CLINICS AND PRACTICE	2039-7275; 2039-7283	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR; Journal Citation Reports - JCR
14560	EUROPEAN JOURNAL OF POST CLASSICAL ARCHAEOLOGIES	2039-7895	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR
14561	AFRICAN JOURNAL OF ECONOMIC AND MANAGEMENT STUDIES	2040-0705; 2040-0713	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR; Journal Citation Reports - JCR
14562	JOURNAL OF DEVELOPMENTAL ORIGINS OF HEALTH AND DISEASE	2040-1744; 2040-1752	A2	Enero 2024 - Junio 2024	Science Citation Index - SCI; Scimago Journal Rank - SJR; Journal Citation Reports - JCR
14563	JOURNAL OF WATER AND CLIMATE CHANGE	2040-2244; 2408-9354	A2	Enero 2024 - Junio 2024	Science Citation Index - SCI; Scimago Journal Rank - SJR; Journal Citation Reports - JCR
14564	JOURNAL OF HEALTHCARE ENGINEERING	2040-2295; 2040-2309	A2	Enero 2024 - Junio 2024	Scimago Journal Rank - SJR