



Predictive Modelling and Low-Flow Augmentation Strategies for the Sota Basin at Coubéri in Benin (West Africa)

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How to cite this paper: Badou, D.F., Hounkpeate, M.U.S.G., Lawin, A.E. and Biao, E.I. (2026) Predictive Modelling and Low-Flow Augmentation Strategies for the Sota Basin at Coubéri in Benin (West Africa). *Journal of Water Resource and Protection*, **18**, 85-101.

<https://doi.org/10.4236/jwarp.2026.182006>

Received: December 24, 2025

Accepted: January 31, 2026

Published: February 3, 2026

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Abstract

This study evaluates a low-flow regulation strategy for the Sota River basin, aiming to maintain a target discharge that satisfies concurrent irrigation demands and ecosystem sustainability. The methodology involved a three-step process: 1) characterizing historical low flows using the annual minimum monthly discharge (QMNA), 2) simulating future discharge regimes using the HEC-HMS hydrological model forced with climate projections bias-corrected via the Distribution Mapping method, and 3) assessing the feasibility of implementing low-flow support measures. Results reveal strong interannual variability in low flows, with two breakpoints in stationarity (1971, 2003) yet no significant monotonic trends within the resulting sub-periods. Frequency analysis identified the Weibull distribution as the best fit, yielding a mean low-flow value of $4.18 \text{ m}^3 \text{ s}^{-1}$. Hydrological simulations from the calibrated HEC-HMS model, which demonstrated reliable performance (Nash-Sutcliffe efficiency, $\text{NSE} = 0.75$ in calibration, 0.70 in validation), project a decline in discharges from 2030 to 2080, with annual reductions of up to 34%. A critical finding emerged from the comparison of climate models: significant divergence exists in the estimated required low-flow support. Projections from the RCA4 model indicate that low-flow augmentation would need to supply between 12% and 39% of the mean annual flow, depending on the ecological flow scenario. In contrast, projections from the CCLM and REMO models suggest a substantially higher requirement, between 30% and 90% of the mean annual flow. This divergence underscores that, while the required volume is model-dependent, the implementation of low-flow support remains a hydro-

logically realistic management objective across the range of climate scenarios evaluated. These findings point to realistic management options for low-flow regulation and contribute to more resilient water resource governance in the Sota basin.

Keywords

Low-Flow Regulation, Ecological Flow, Weibull Distribution, HEC-HMS, Sota River Basin

1. Introduction

Water resources management faces a major challenge: satisfying a growing demand while coping with the consequences of increased climate variability, manifested in more frequent and intense drought episodes [1] [2]. At the global scale, these drought episodes result in critically low river flows, which strongly disrupt local economic activities as well as the proper functioning of ecosystems.

This is exemplified in the Amazon Basin, where [3] demonstrated that severe droughts reduce river navigability and isolate communities. In Europe, [4] showed that hydrological drought could, in the most affected regions (southern, south-eastern, and western Europe), lead to economic losses equivalent to up to 2% of the regional gross domestic product, while the agricultural sector could lose 15% of its gross value added. Similarly, [5] found an increasing trend in drought phenomena across sub-Saharan Africa, resulting in the drying up of water sources, the disappearance of pastures, crop losses, food shortages, and rising food prices. Against this background another example is given by the 2019 drought in Southern Africa which led to severe food insecurity, malnutrition and various health problems affecting 45 million people, in Zambia, Zimbabwe, and South Africa [6] [7].

In West Africa, too, previous studies [8]-[10] have highlighted a significant decline in precipitation during the 1970s and 1980s, leading to a critical drop in river flows and staple crop yields, causing acute episodes of food shortage [11]-[13].

To better understand and manage such crises, extensive research has been conducted [1] [14]-[18] to deepen our knowledge on low-flow phenomena and to develop flow-regulation strategies aimed at optimizing water usages.

The Sota Basin, a sub-basin of the Niger River, is experiencing a progressive reduction in flows, which has compelled local authorities to promote the construction of small dams primarily for livestock watering, crop irrigation, and fish farming [19]-[21]. While these small dams alleviate the issue locally, especially in the upper part of the basin, a continuous decline in low-flow discharges is observed downstream, falling below the intake levels of surface-water pumping stations and thereby compromising their use for irrigation. Similarly, river navigation is hindered and the functioning of aquatic ecosystems is altered. Despite this

situation, knowledge on low-flow dynamics and the impacts of climate change on their occurrence and intensity remains limited in this basin [10] [22].

This study therefore seeks to address these gaps, with the primary objectives of characterizing historical low flows using the annual minimum monthly discharge (QMNA) indicator, simulating future flows under different climate scenarios, and assessing the feasibility of low-flow regulation through hydraulic infrastructures.

2. Materials and Methods

2.1. Research Area

Located in northeastern Benin, between the geographical coordinates $9^{\circ}52'$ and $11^{\circ}51'$ North latitude and $2^{\circ}34'$ and $3^{\circ}46'$ East longitude, the Sota River basin at the Coubéri outlet is a sub-basin of the Niger River and covers a total area of 13432.5 km^2 (Figure 1).

The basin experiences a Sudano-Sahelian climate, characterized by a unimodal rainfall regime with a single rainy season from April to October. The mean annual rainfall is 936 mm [8], and average temperatures range between 19°C and 37°C . Administratively, the basin spans seven municipalities: Bembèrèkè, Gogounou, Kalalé, Kandi, Malanville, Nikki, and Ségbana. The population of the Sota basin is estimated at 870,511 inhabitants, with an economy primarily based on agricultural activities and livestock farming.

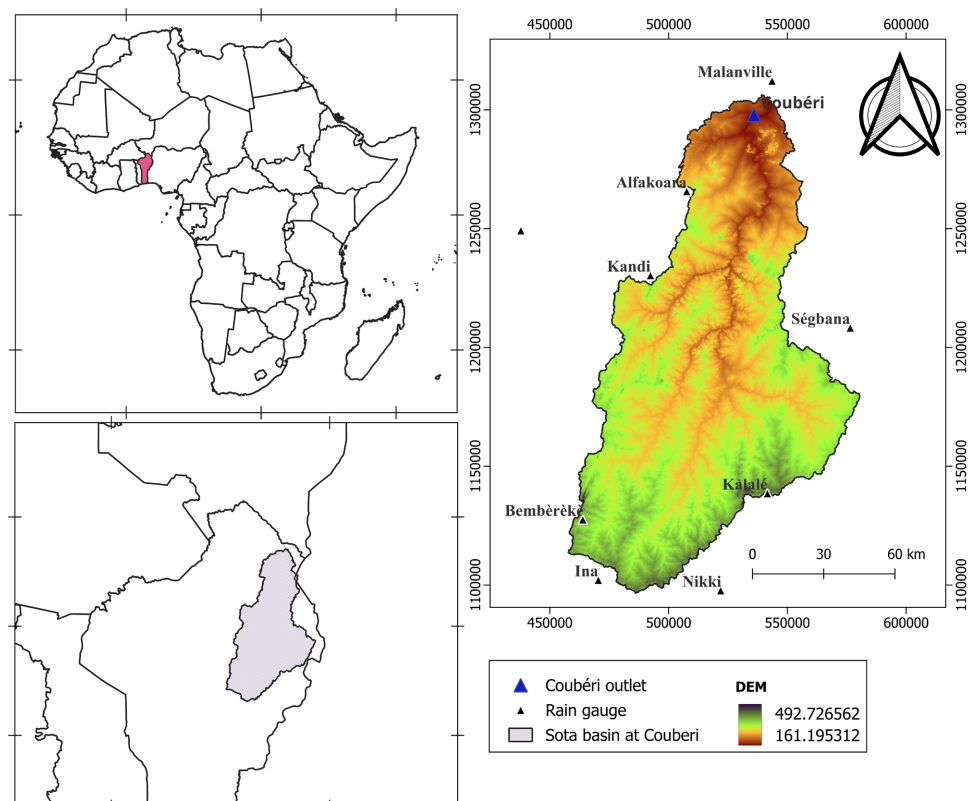


Figure 1. Location of the study area and gauging stations.

2.2. Data

The hydroclimatic data used originate from multiple sources. Daily precipitation data were obtained from nine rain gauges installed within the Sota Basin, while temperature (minimum and maximum) and potential evapotranspiration data came from the Kandi synoptic station. All observational data were provided by the Benin Meteorological Agency for the period 1970–2020. Daily discharge data at the Coubéri gauging station were sourced from the database of the General Directorate of Water (DG-Eau) for the period 1953–2017. Additionally, daily precipitation, minimum temperature, and maximum temperature from three regional climate model (RCM) were used (Table 1). These models are part of the CORDEX-Africa (AFR-44) program, which provides data at a spatial resolution of 0.44° and covers a geographical domain extending from 24.64°W to 60.28°E in longitude and from 45.76°S to 42.24°N in latitude [23]. The RCP4.5 and RCP8.5 scenarios were considered for the RCMs' outputs.

Table 1. Regional climate models (RCMs) and their driving global circulation models (GCMs).

RCM	GCM	Centre
CCLM	MPI-ESM-LR	Max Planck Institute (MPI)
RCA	NOAA-GFDL-ESM2M	Swedish Institute of Meteorology and Hydrology (SMHI)
REMO	MPI-ESM-LR	Max Planck Institute (MPI)

2.3. Methods

2.3.1. Characterizing Low Flows

The characterization of low flows in this study is based on the QMNA which is the lowest monthly flow observed in a given hydrological year. It is derived by calculating the monthly mean discharges and then extracting the minimum value for each year within the study period. This index (Equation (1)) is widely used in hydrology to quantify the intensity of low-flow events and capture their variability [24]–[26].

$$QMNA = \min \left(\frac{1}{n_m} \sum_{j=1}^{n_m} Q_{m,j}^i \right) \quad (1)$$

where $Q_{m,j}^i$ is the daily discharge for day j of month m in year i ; n_m is the number of days in month m .

To detect potential changes in the QMNA time series, three statistical tests were applied:

- the Pettitt test, used to identify breakpoints in the series,
- the Mann-Kendall test, employed to detect monotonic trends, and
- the Sen's slope estimator, applied to quantify the magnitude of any detected trend.

In addition, a frequency analysis of the QMNA series was performed using four

probability distributions: Weibull, Gumbel, Gamma, and Lognormal. The goodness-of-fit of these distributions was evaluated based on the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC), which allow for the selection of the most appropriate statistical model to represent the low-flow distribution. The best-performing distribution is the one associated with the lowest AIC and BIC values [27] [28].

2.3.2. Climate Data Pre-Processing

Regional climate model outputs typically exhibit systematic biases that may affect hydrological simulations, thereby necessitating the application of correction methods prior to their use [29] [30].

Accordingly, during the pre-processing phase, data from the RCMs were subjected to bias correction to reduce systematic deviations from observed data. To this end, the Distribution Mapping (DM) method, implemented in the CMhyd software package [29], was employed. This method adjusts the empirical distribution function of simulated data to that of observations according to Equation (2):

$$x_{corr} = F_{obs}^{-1}(F_{sim}(x_{sim})) \quad (2)$$

where x_{sim} denotes the raw simulated value, F_{sim} its cumulative distribution function, F_{obs}^{-1} the inverse of the observed distribution, and x_{corr} the bias-corrected value.

The quality of the bias-corrected series was subsequently evaluated using Taylor diagrams, which synthesize the correlation coefficient, standard deviation, and normalized root mean square error between corrected simulations and observations [31].

2.3.3. Discharge Modelling

Hydrological modeling was performed using the HEC-HMS (Hydrologic Engineering Center-Hydrologic Modeling System) software, widely employed to simulate the hydrological response of watersheds [32] [33]. The conceptual framework adopted consists of a combination of sub-models tailored to the characteristics of the Sota River basin:

- Canopy method: Simple Canopy
- Surface method: Simple Surface
- Loss method: Soil Moisture Accounting (SMA)
- Transform method: SCS Unit Hydrograph
- Baseflow method: Constant Monthly

The model was calibrated and validated over the historical periods 1998-2006 and 2010-2016, respectively, using observed discharge data from the Coubéri gauging station. Simulation quality was assessed using the Nash-Sutcliffe Efficiency (NSE) and Root Mean Square Error (RMSE) statistical metrics [34].

Once satisfactory model performance was established, bias-corrected climate projections (RCP4.5 and RCP8.5) derived from the three RCMs were utilized as forcing data to simulate future discharges over the 2030-2080 period.

The percentage change in future mean annual discharge relative to the histori-

cal mean is given by the Equation (3):

$$P_i = \frac{Q_i - \overline{Q_{hist}}}{\overline{Q_{hist}}} \times 100 \quad (3)$$

where Q_i is the future mean annual change of a given year, and $\overline{Q_{hist}}$ the mean annual over the historical period.

2.3.4. Determination of Ecological Flow, Irrigation Water Requirements, and Low-Flow Augmentation Discharge

The objective of this phase was to determine, based on historical and future daily discharge time series, the capacity of a reservoir to augment low flows through controlled releases during the dry season, thereby ensuring ecological flow requirements and satisfying irrigation water demands.

Ecological flow (Q_{eco}) is defined as the discharge required to maintain aquatic ecosystem functioning at an acceptable level [35].

Following the Tennant method [36], three ecological flow scenarios were analyzed:

- 1) a minimalist scenario for aquatic ecosystem survival, wherein ecological flow corresponds to 10% of mean annual discharge, representing the threshold below which ecosystem survival is compromised;
- 2) an intermediate scenario wherein ecological flow equals 30% of mean annual discharge, considered “excellent” for ecological health; and
- 3) a third optimal scenario wherein environmental flow corresponds to 60% of mean annual discharge, associated with optimal conditions for ecosystem health.

The mean annual discharge used to establish the minimal, intermediate, and optimal flow thresholds according to the Tennant method was computed from the historical flow data.

Data on irrigation water requirements were extracted from the Water Master Plan for the Beninese portion of the Niger River basin [37]. Two major crops were considered: rice and tomato, with a total projected irrigated area of 7895 ha. For these two crops, the dry season production cycle (December to March) requires water demands of 11,817 m³/ha for rice and 11,600 m³/ha for tomato. The average of these two water requirements (which are close) was adopted due to the lack of detailed land use [37].

Monthly irrigation water requirements were converted to irrigation discharge $Q_{irr}(m)$. Thus, for each month m of the low-flow period, the target discharge $Q_t(m)$, to meet irrigation and ecosystem needs, is given by:

$$Q_t(m) = Q_{eco} + Q_{irr}(m) \quad (4)$$

The discharge required for low-flow augmentation ($Q_{regulation}(m)$) is therefore the difference between the target monthly discharge and the projected mean monthly discharge ($Q_{proj}(m)$). It follows that:

$$Q_{regulation}(m) = \max(Q_t(m) - Q_{proj}(m), 0) \quad (5)$$

and the volume of water required for low-flow augmentation ($V_{regulation}(m)$)

$$V_{regulation}(m) = Q_{regulation}(m) \times 86400 \times N_{days}(m) \quad (6)$$

where $N_{days}(m)$ represents the number of days per month during the low-flow period and 86,400 is a constant to convert discharge in m^3/s to volume in m^3 .

Consequently, for each ecological flow scenario, the active storage volume V_u required for low-flow augmentation is derived as:

$$V_u = \sum_{m=1}^6 V_{regulation}(m) \quad (7)$$

V_u represents water to be supplied at the Couberi outlet, not the volume of a specific reservoir.

Afterward, the comparison between low-flow augmentation discharge and projected mean monthly discharge enables quantification of their relationship as a percentage.

3. Results and Discussion

3.1. Low Flow Characteristics

The evolution of the Pettitt's test U-statistic applied to the QMNA indices exhibits an increasing trend from 1954 to 1971, characterized by a progressive rise in statistical values up to the first breakpoint (**Figure 2**). This is followed by a gradual decline in the test statistic, reaching a marked minimum in 2003, before subsequently increasing again through 2016. These discontinuities correspond respectively to the major Sahelian drought of the early 1970s documented in several studies [8] [22] [38] and to a more recent period towards a recovery.

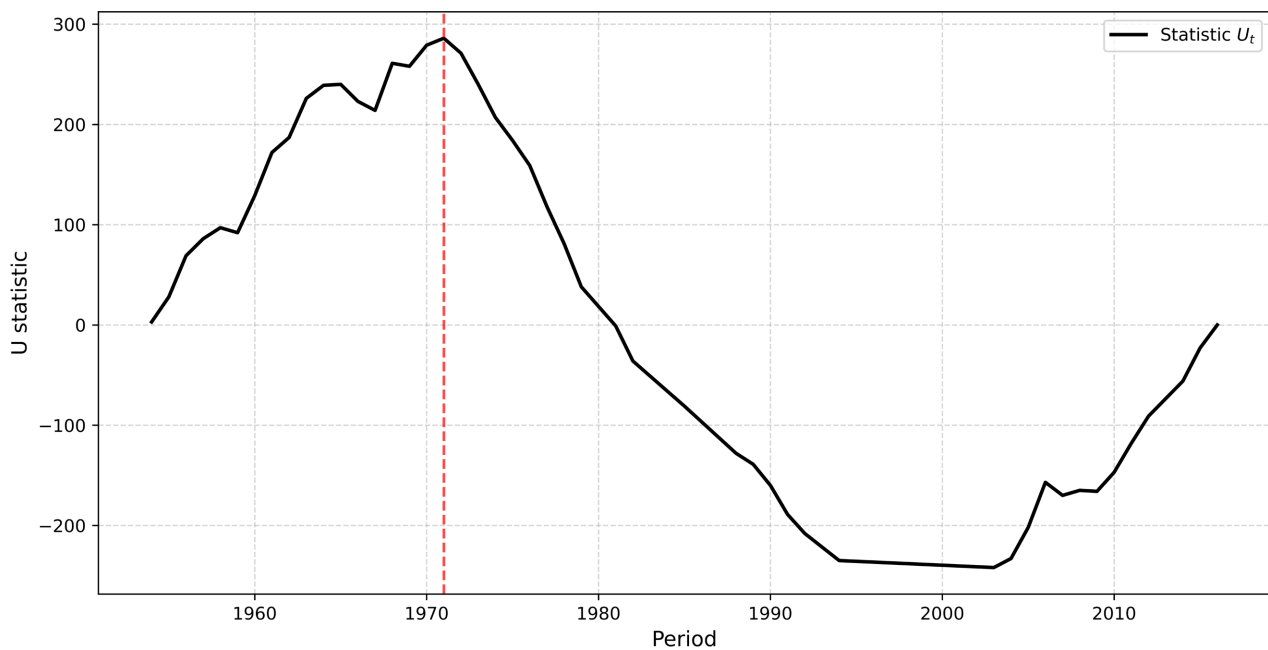


Figure 2. Evolution of the Pettitt test U statistic for the QMNA series.

However, Mann Kendall and Sen’s slope tests applied to the sub-periods delineated by these breakpoints indicate no statistically significant trends (**Table 2**), suggesting pronounced interannual variability in low flows without a clear long-term trajectory.

Table 2. Statistics from the Mann-Kendall test and Sen’s slope estimator.

Sub-period	Kendall’s tau	p-value	Sen’s slope	Significance (5%)
1954-1970	−0.132	0.4838	−0.0258	No
1971-2002	−0.137	0.4487	−0.0324	No
2003-2016	0.308	0.1606	0.0998	No

From a frequency analysis perspective, the fitting of statistical distributions to observed values demonstrates that all four distributions somehow fit the QMNA series (**Figure 3**), although the Weibull distribution provides a superior fit to the data in terms of AIC and BIC information criteria (**Table 3**). This performance is consistent with previous studies on extreme flows in Sahelian regions, where the Weibull distribution is frequently favored for modeling low flow quantiles [11] [39].

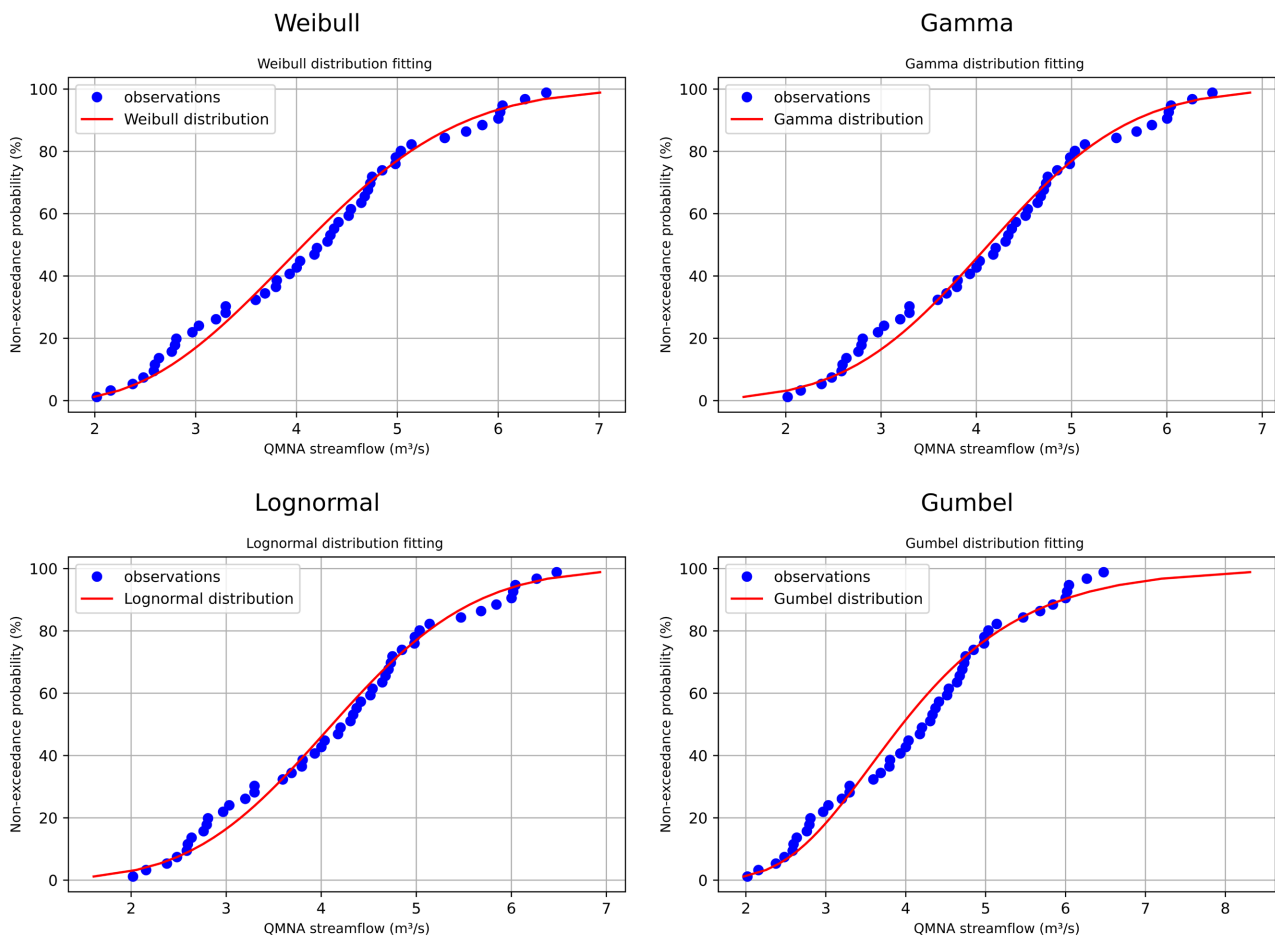


Figure 3. Goodness-of-fit of distribution functions to the QMNA series.

Table 3. BIC and AIC values for the distribution functions fitted to the QMNA series.

Distribution function	IC	AIC
Weibull	158.527	154.784
Gamma	159.464	155.721
Lognormale	161.068	157.326
Gumbel	162.277	158.534

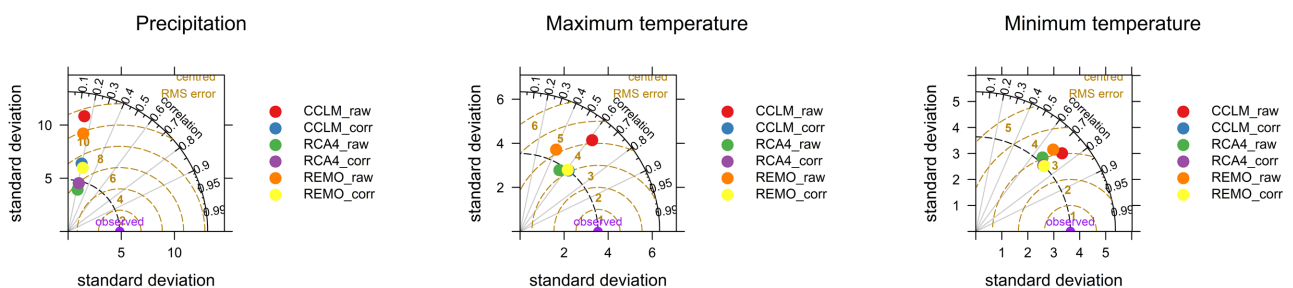
Furthermore, quantile analysis for different return periods confirms the inverse relationship between return period and low-flow severity, thereby highlighting the basin's increased vulnerability to severe low flows during extreme events (**Table 4**).

Table 4. Characteristic low-flow values for different return periods.

T (years)	F	Q _T (m ³ /s)	Standard deviation (m ³ /s)	Confidence interval (95%)
2	0.5	4.18	0.179	[3.83; 4.53]
5	0.2	3.14	0.206	[2.74; 3.55]
10	0.1	2.6	0.219	[2.17; 3.03]
20	0.05	2.17	0.223	[1.73; 2.61]
50	0.02	1.71	0.219	[1.28; 2.15]
100	0.01	1.44	0.211	[1.02; 1.85]

3.2. Bias-Corrected Future Climate Data

Raw and bias-corrected precipitation and temperature simulations from the three RCMs are compared with observations using Taylor diagrams (**Figure 4**).

**Figure 4.** Taylor diagram showing bias correction performance for RCM data.

The Distribution Mapping technique proved particularly effective for correcting temperature data biases, ensuring better representation of thermal conditions, whereas precipitation showed less precise corrections. Specifically, the CCLM bias corrected data are the closest to the observations, with very similar standard deviation and high correlation coefficient (exceeding 0.95). The corrected data from the RCA4 and REMO models are somewhat more distant from observations with slightly lower standard deviations than those of observations, but correlation re-

mains highly satisfactory (greater than or equal to 0.85), reflecting notable improvement compared to the raw data.

This disparity is common in statistical correction approaches, as precipitation is often more challenging to model accurately due to its high spatial and temporal variability.

The observed and simulated hydrographs from the HEC-HMS model for the calibration and validation periods (**Figure 5**) show a good reproduction of seasonal and interannual dynamics. Simulation quality is confirmed by NSE values (0.75 during calibration and 0.70 during validation). However, the model exhibits intensity biases, with a tendency to underestimate low flow at the beginning of the rainy season (e.g. 1998, 1999, 2010 and 2014) and to overestimate flood peaks in some years (2002, 2011, and 2014) and to occasionally underestimate them (2004 and 2013).

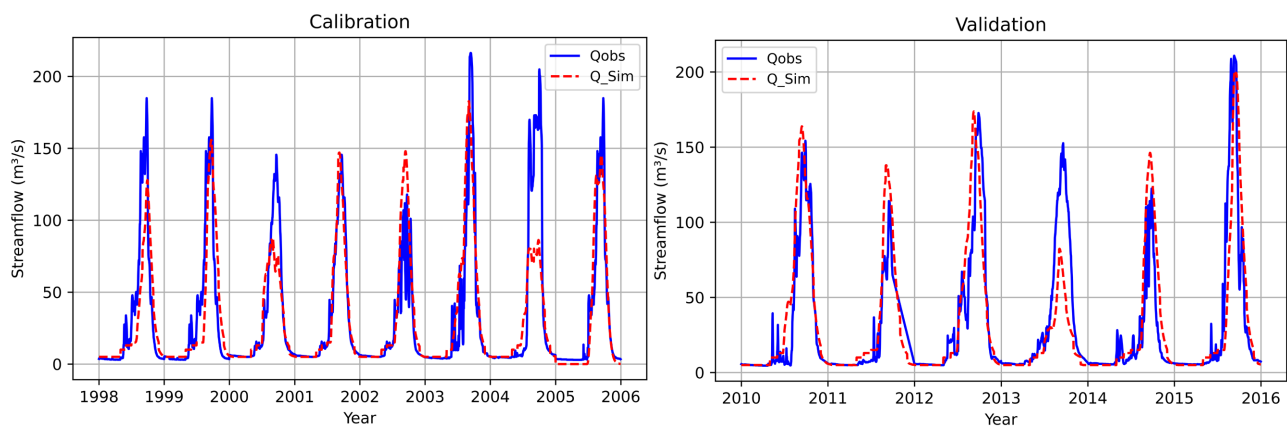


Figure 5. Hydrographs of observed and simulated discharges during calibration and validation periods.

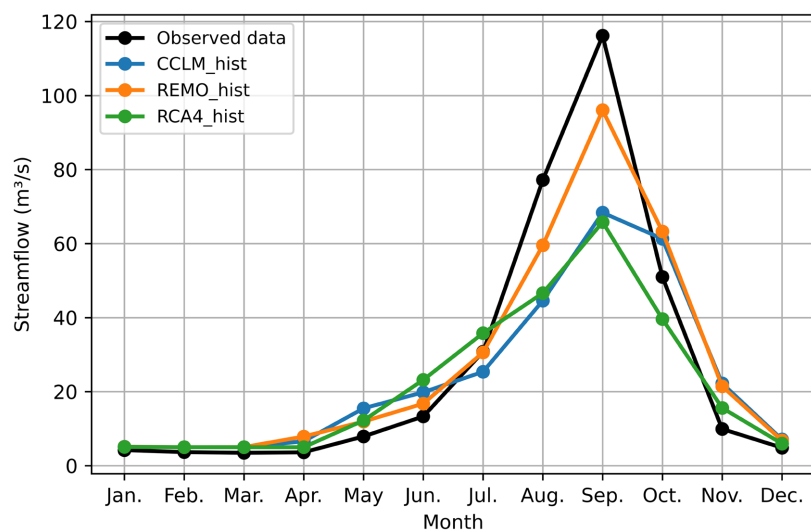


Figure 6. Hydrographs of future projected discharges.

Bias-corrected climate data from the RCMs served as inputs to the HEC-HMS

model to simulate future discharges. Inspection of these discharges over the historical period (1970–2005) shows that all three datasets adequately simulate the seasonal pattern of observed flow, with low flows between December and May and flood peaks in September (**Figure 6**). Irrespective of the RCM considered, low flows are well simulated while flood peaks are underestimated under the CCLM and RCA4 models.

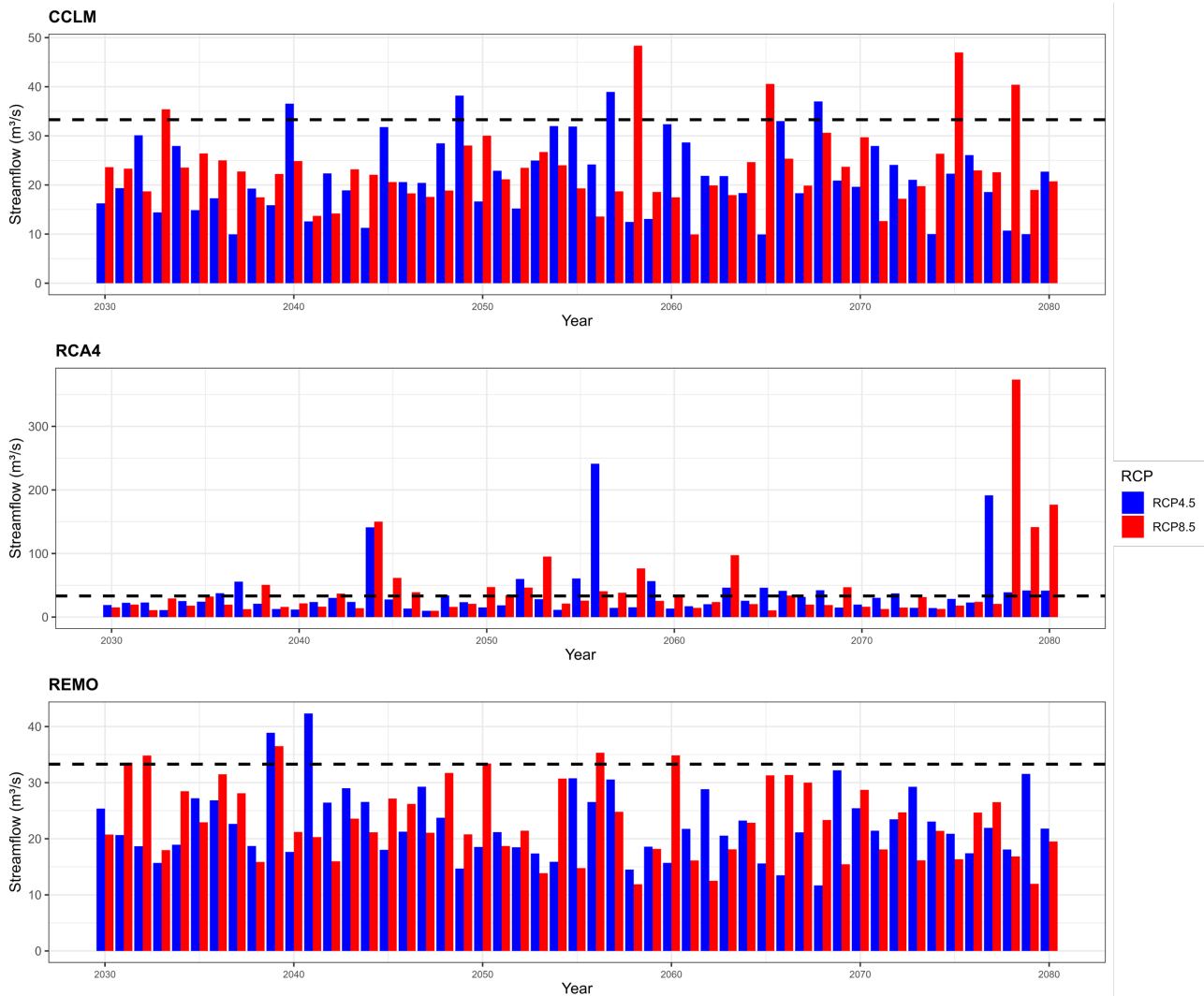


Figure 7. Interannual variability of future discharges under RCP 4.5 and RCP 8.5 scenarios.

Projections from the CCLM and REMO models indicate a general declining trend in future annual discharges, with reductions ranging from -29% to -34% relative to the reference period (**Figure 7**). This trend toward markedly lower annual flows corroborates projections of increasing water stress reported for other West African basins [15] [33], posing significant challenges for meeting agricultural, domestic, and ecological water demands. In contrast, projections from the RCA4 RCM suggest an increase in annual discharge of up to $+12\%$ (RCP4.5) and

+31% (RCP8.5). This inter-model discharge variability stems from well-documented uncertainties in projecting the frequency and magnitude of extreme rainfall events, which propagate in simulated flows [1] [40].

3.3. Feasibility of Low-Flow Augmentation in the Future

Table 5 presents low-flow augmentation requirements according to the three ecological flow scenarios considered in this study.

Table 5. Discharge and active storage volume for low-flow augmentation according to ecological flow maintenance scenarios, climate models, and climate scenarios considered in this study.

Scenario	Variable	CCLM ^a	CCLM ^b	REMO ^a	REMO ^b	RCA4 ^a	RCA4 ^b
Minimal	$Q_{regulation}$ (m ³ /s)	6.65	6.50	6.99	6.97	5.32	5.49
	% of module	30.45	27.79	30.90	30.03	14.33	12.57
	V_u (10 ⁶ m ³ /an)	69.23	67.55	72.84	72.63	54.97	56.73
intermediate	$Q_{regulation}$ (m ³ /s)	9.88	10.11	10.31	10.46	7.76	7.44
	% of module	45.22	43.25	45.58	45.07	20.89	17.04
	V_u (10 ⁶ m ³ /an)	154.62	158.33	161.62	163.94	120.95	115.73
optimal	$Q_{regulation}$ (m ³ /s)	19.86	20.10	20.30	20.45	14.42	14.09
	% of module	90.93	85.97	89.72	88.10	38.81	32.29
	V_u (10 ⁶ m ³ /an)	311.67	315.37	318.66	320.98	225.36	220.13

a. RCP 4.5 b. RCP 8.5.

Results reveal substantial differences among RCMs regarding future low-flow augmentation requirements. The CCLM and REMO models project higher requirements, with augmentation discharges ranging from 6 to 20 m³/s depending on the augmentation level. Conversely, RCA4 indicates lower requirements ranging from 5 to 14 m³/s, reflecting less severe low flows in its projections. Nevertheless, our results align with the work of [41] on several rivers with environmental flow estimated at 20 m³/s.

The augmentation discharges obtained in this study correspond to a percentage of mean annual discharge varying between 13% and 30% for the minimalist scenario, 17% and 46% for the intermediate scenario, and 32% and 91% for the optimal scenario. These proportions fall within the ranges observed in other basins with similar characteristics. For instance, the International Water Management Institute [42] reports that 60-80% of the mean annual flow is needed to maintain a river in a natural state. Assessing the sustainability of the lower Limpopo River basin, [43] found that environmental flows correspond to approximately 50%, 39%, 27%, and 14% of the mean annual flow for excellent, medium, poor, and degraded scenarios, respectively. [44] using five methods including Tennant's method, indicated that 46% - 71% of the mean annual flow is necessary to meet environmental needs during low-flow periods. In contrast, [45] estimated envi-

ronmental flows at 20% - 30% of the mean annual flow during low-flow months for the Amu Darya River, and [46] estimated the minimum ecological flow for the Hulan River at 10% of the natural flow.

In terms of storage volume required for augmentation, results from this study range from 55 to 73×10^6 m³/year for minimal augmentation, 116 to 164×10^6 m³/year for moderate augmentation, and 220 to 321×10^6 m³/year for optimal augmentation. According to the Water Master Plan for the Niger basin in Benin, the mean annual volume for the Sota basin at Coubéri is estimated at 946.1×10^6 m³/year [37], implying that the augmentation volumes estimated in this work represent less than one-third of the total annual available water resource. Therefore, the tested regulation strategies remain hydrologically realistic, but the primary challenge lies in the seasonal variability of flows.

Moreover, the analysis of the drying climate projections (CCLM and REMO) indicates that wet-season water availability is sufficient to fully meet the storage requirements for both minimal and intermediate flow augmentation scenarios across all years. For the optimal flow augmentation scenario, storage capacity cannot be met in a small subset of exceptionally dry years: in up to 12% of years under the CCLM_RCP4.5 projection and fewer than 6% of years in the other model-scenario combinations. From an operational perspective, targeting the intermediate flow regulation scenario would be the prudent management strategy during these extreme dry years.

Overall, these results indicate that low-flow augmentation is largely feasible even under drying climate conditions, with only limited risk of failing to meet the most ambitious (optimal) scenario.

4. Conclusions

This research aimed to evaluate the extent to which a storage facility could contribute to low-flow augmentation in the Sota basin at Coubéri. The analysis focused on reconciling two essential dimensions: agricultural water requirements and ecological imperatives.

The results indicate that low flows have experienced two stationary breakpoints (1971 and 2003) and that the Weibull distribution best describes their distribution, with a mean low-flow discharge estimated at 4.18 m³/s. The HEC-HMS model demonstrated satisfactory performance (NSE of 0.75 during calibration and 0.70 during validation). Climate projections, bias-corrected using the Distribution Mapping method, indicate a general downward trend in annual discharges for the period 2030-2080, with reductions potentially reaching -34%, while also projecting increased interannual variability marked by extreme hydrological events.

Based on these findings, the ecological flow was assessed according to three scenarios (minimalist, intermediate, and optimal) inspired by Tennant's method. The estimated active storage volumes, which could reach up to 321×10^6 m³/year for optimal low-flow augmentation, highlight a significant risk of future water

stress during dry seasons if no mitigation measures are implemented. However, when contextualized within the water availability projections of the basin's Water Master Plan, these results suggest that low-flow augmentation remains a feasible objective across the range of ecological flow and climate scenarios considered.

The present study focuses on establishing the hydrological feasibility and magnitude of required active storage volumes under climate change scenarios to support low-flow augmentation in the Sota basin. While our analysis demonstrates that such volumes remain within realistic ranges across multiple climate projections, the detailed infrastructure design and assessment of optimal spatial configuration, including multi-criteria evaluation of single versus distributed storage options, siting analysis, and evaporation loss modeling, represents a critical avenue for future research. Such investigations would need to integrate hydrological, socio-economic, and environmental considerations to guide practical implementation of low-flow augmentation strategies.

Overall, this study primarily underscores the vulnerability of the Sota basin to water shortages during low-flow periods. It emphasizes the urgency of adopting integrated water resources management that combines rigorous hydrological analysis, ecosystem preservation, and the accommodation of human water needs. The future resilience of the hydrological system fundamentally depends on achieving this balance.

Acknowledgements

The authors gratefully acknowledge the farmers of Malanville for their invaluable contribution in sharing data and insights on local rice-growing practices during fieldwork.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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