



(RESEARCH ARTICLE)



INTEGRATED HYDROLOGICAL ASSESSMENT FOR THE DESIGN OF A MULTIPURPOSE SMALL RESERVOIR IN THE SIRBA RIVER BASIN, NIGER

HAROUNA Souley¹, MAMAN HASSAN Abdourazakou^{2,*}, ELHADJI DAOU IBRAHIM³, Mahamane Moustapha Sanda Chékaraou⁴, Karimou Laouali Idi⁵ and Badamassi Kadri Mahaman Mansour⁶

¹ School of Mines, Industry and Geology of Niamey (EMIG), Department of Civil Engineering, Niamey, Niger.

² School of Mines, Industry and Geology of Niamey (EMIG), Department of Mines-Geology, Niamey, Niger.

³ School of Mines, Industry and Geology of Niamey (EMIG), Department of Mining Engineering and Environment, Niamey, Niger.

⁴ Djibo Hamani University of Tahoua, Faculty of Education Sciences, Department of Discipline Didactics, Tahoua-Niger.

⁵ Department of SVT, Abdou Moumouni University, Higher Normal School, Niamey, Niger.

⁶ Department of Geological and Environmental Sciences, Faculty of Sciences and Techniques, Georesources and Environmental Geosciences Laboratory, André Salifou University of Zinder (UAS).

* Corresponding Author

ORCID Details

HAROUNA Souley: <https://orcid.org/0009-0002-9055-7306>

MAMAN HASSAN Abdourazakou: <https://orcid.org/0000-0003-1452-4115>

ELHADJI DAOU IBRAHIM: <https://orcid.org/0009-0004-4185-9708>

Mahamane Moustapha Sanda Chékaraou: <https://orcid.org/0000-0001-8378-7205>

Karimou Laouali Idi: <https://orcid.org/0009-0000-2825-2777>

World Journal of Advanced Research and Reviews, 2026, 32(01), 483–499

Publication history: Received on 26 August 2026; revised on 02 October 2026; accepted on 05 October 2026

Article DOI: <https://doi.org/10.30574/wjarr.2026.32.1.2133>

Copyright © 2026 Author(s) retain the copyright of this article. This article is published under the terms of the Creative Commons Attribution License 4.0

ABSTRACT

Water scarcity and increasing hydroclimatic variability represent major constraints to sustainable development in the Sahel, where rural livelihoods depend largely on rain-fed agriculture and seasonal water availability. In southwestern Niger, the Sirba River watershed experiences recurrent floods during the rainy season and severe water shortages during the prolonged dry season, highlighting the need for efficient water storage infrastructures. This study assessed the hydrological feasibility of constructing a multipurpose small dam in the Sirba River watershed using an integrated hydrological and geomorphological approach. Long-term rainfall and hydrological data (1960-2020), a 30-m Shuttle Radar Topography Mission (SRTM) Digital Elevation Model, Geographic Information Systems (GIS), and regional empirical hydrological methods (ORSTOM, CIEH and Gradex) were employed to characterize the watershed, estimate design floods and evaluate the reservoir water balance. Rainfall frequency analysis using the Generalized Extreme Value (GEV) distribution indicated design rainfall depths ranging from 210 mm for the 5-year return period to 289 mm for the 100-year return period. Morphometric analysis showed that the watershed covers 39091 km², with an elongated geometry (Gravelius coefficient = 2.04) and a low drainage density (0.06 km km⁻²), characteristics that contribute to moderate flood concentration. The estimated 10-year design flood reached 100.04 m³ s⁻¹, while the mean annual runoff

volume was estimated at $86.12 \times 10^6 \text{ m}^3$, decreasing to $40.36.10^6 \text{ m}^3$ under 10-year dry conditions. Although evaporation and sedimentation constitute the principal water losses, the reservoir water balance remained positive under average hydrological conditions, indicating sufficient water availability to satisfy projected domestic, livestock and agricultural demands. Overall, the results demonstrate that the proposed small dam is hydrologically feasible and could significantly enhance water security, support irrigated agriculture, reduce flood risks and strengthen climate resilience in the Sirba River watershed. Future studies should incorporate physically based hydrological modelling, sediment yield assessment and climate change scenarios to optimize reservoir design and long-term operation.

Keywords: Hydrological Feasibility; Small Dam; Sirba River; Sahel; Water Ressources Management

1 INTRODUCTION

Freshwater availability has become one of the most critical challenges facing sustainable development worldwide. Rapid population growth, increasing food demand, land-use change, and the intensification of climate variability have substantially altered hydrological regimes, particularly in semi-arid and arid regions. According to the Intergovernmental Panel on Climate Change (IPCC), climate change has increased the frequency and intensity of both droughts and extreme rainfall events, thereby exacerbating water insecurity and increasing the vulnerability of water-dependent sectors such as agriculture, livestock production, and domestic water supply (**IPCC, 2023**). Consequently, improving water resources management has become a strategic priority for achieving the Sustainable Development Goals (SDGs), especially SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 13 (Climate Action) (**United Nations, 2023**).

Among the numerous adaptation strategies proposed to address growing water scarcity, the construction and rehabilitation of small reservoirs have attracted considerable attention. Small dams provide multiple ecosystem services by regulating runoff, reducing flood peaks, increasing groundwater recharge, supporting irrigated agriculture, ensuring livestock watering, and enhancing local socioeconomic resilience (**FAO, 2022**). Compared with large dams, small reservoirs generally require lower investment costs, have fewer environmental impacts, and are more suitable for decentralized rural development, particularly in Sub-Saharan Africa where rainfall is highly seasonal and water availability remains unevenly distributed throughout the year (**World Bank, 2023**).

However, the long-term sustainability of small reservoirs largely depends on the reliability of hydrological assessments performed during the planning stage. Poor estimation of design floods, reservoir inflows, sediment transport, and water losses frequently results in structural failure, reservoir underperformance, or inadequate water storage capacity. Consequently, hydrological feasibility studies constitute the cornerstone of sustainable reservoir planning because they allow engineers to characterize watershed behavior, estimate hydrological extremes, and optimize reservoir dimensions under current and future climatic conditions (**Mashauri et al., 2022**).

Across Africa, climate variability poses unprecedented challenges for water resources management. The African continent has experienced increasing hydroclimatic extremes over recent decades, characterized by longer drought periods interrupted by more intense rainfall events. These changes have modified runoff generation processes, increased flood hazards, accelerated soil erosion, and reduced the reliability of traditional water storage systems (**WMO, 2023**). Such changes are particularly evident within the Sahel, where rainfall variability remains among the highest in the world.

The Sahelian region has undergone profound hydroclimatic transformations since the severe droughts of the 1970s and 1980s. Although annual rainfall has partially recovered during the last three decades, recent studies indicate that rainfall events have become increasingly concentrated into short-duration storms producing exceptionally high runoff coefficients and devastating flash floods (**Panthou et al., 2021; Descroix et al., 2021**). This apparent paradox-known as the "Sahelian hydrological paradox"-reflects the increasing occurrence of floods despite only moderate recovery of annual precipitation. Land degradation, vegetation loss, soil crusting, agricultural expansion, and urbanization have considerably increased runoff production throughout many Sahelian watersheds (**Aich et al., 2022**).

Within this context, small dams are increasingly recognized as essential climate adaptation infrastructures capable of buffering seasonal rainfall variability while supporting agricultural intensification and improving rural livelihoods (**FAO, 2022**). Nevertheless, several studies have emphasized that numerous small reservoirs constructed across West Africa suffer from sedimentation, inadequate spillway design, insufficient storage capacity, or poor estimation of design floods due to limited hydrological information and the predominance of ungauged catchments (**World Bank, 2023**). These challenges underline the importance of employing robust hydrological approaches that integrate rainfall frequency analysis, watershed morphometric characterization, flood estimation methods, and reservoir water balance assessments.

In West Africa, the Niger River Basin represents one of the continent's most important transboundary river systems, supporting more than 160 million inhabitants distributed across nine countries. Water resources within this basin sustain agriculture, hydropower generation, fisheries, domestic water supply, ecosystem conservation, and livestock production (**Niger Basin Authority, 2023**). However, increasing climatic variability combined with rapid demographic growth has intensified pressure on available water resources, thereby increasing competition among different water users.

Among the major tributaries of the Middle Niger River, the Sirba River occupies a strategic position because of its dual hydrological behavior. During the rainy season, the river frequently generates destructive floods affecting downstream communities, whereas during the prolonged dry season water availability becomes extremely limited for agricultural and pastoral activities (**Tiepolo et al., 2021**). Recent flood events have demonstrated the growing vulnerability of settlements located along the Sirba floodplain, particularly within southwestern Niger, where repeated inundations have caused severe socioeconomic losses, displacement of populations, destruction of infrastructure, and degradation of agricultural land (**ANADIA 2.0 Consortium, 2022**).

Hydrological monitoring conducted over the last decade further indicates that flood magnitudes within the Sirba basin have increased significantly, partly due to intensified rainfall events and land-use changes occurring upstream in Burkina Faso and Niger (**Souley Tangam et al., 2024**). These findings reinforce the necessity of implementing hydraulic infrastructures capable of simultaneously mitigating flood risks and securing water availability during prolonged dry periods.

In Niger, agriculture contributes substantially to national employment and household income, yet remains highly dependent on erratic rainfall. More than 80% of cultivated land relies exclusively on rain-fed agriculture, making rural livelihoods particularly sensitive to climatic fluctuations (World Bank, 2023). Water storage infrastructures therefore constitute one of the government's principal adaptation strategies to strengthen food security, expand irrigated agriculture, improve livestock production, and reduce poverty.

The development of small dams has consequently become a national priority within Niger's Integrated Water Resources Management framework. Nevertheless, successful implementation requires rigorous technical investigations capable of accurately quantifying available water resources while ensuring infrastructure safety under extreme hydrological conditions. Hydrological feasibility studies must therefore integrate rainfall variability analysis, watershed morphometric characterization, frequency analysis of extreme precipitation, runoff estimation, reservoir storage assessment, evaporation losses, infiltration processes, and projected water demand.

Despite increasing research efforts devoted to the Sirba watershed, several scientific gaps remain. Most previous investigations have primarily focused on flood forecasting, hydraulic modelling, or early warning systems, while relatively few studies have comprehensively evaluated the hydrological feasibility of small reservoir development using an integrated watershed-based approach. Furthermore, uncertainties associated with rainfall frequency analysis, design flood estimation for ungauged catchments, and long-term water balance assessment continue to represent important limitations for hydraulic planning in the basin (**Souley Tangam et al., 2024**).

Addressing these knowledge gaps is essential for improving engineering design and supporting evidence-based water resources management in southwestern Niger. Integrating statistical rainfall analysis with watershed morphometry, empirical flood estimation methods, and reservoir water balance calculations provides a scientifically robust framework for evaluating reservoir feasibility under current hydroclimatic conditions.

Therefore, the present study aims to assess the hydrological feasibility of constructing a small dam on the Sirba River in southwestern Niger through a comprehensive characterization of the watershed hydrology and reservoir water balance. Overall, this research contributes to strengthening scientific knowledge regarding hydrological feasibility assessment of small reservoirs in semi-arid West Africa. The findings are expected to support decision-makers, engineers, and water resource managers involved in climate adaptation planning, integrated watershed management, and sustainable hydraulic infrastructure development in Niger and comparable Sahelian environments.

2 MATERIALS AND METHODS

2.1 Study Area

The present study was conducted in the Sirba River watershed, a major right-bank tributary of the Middle Niger River located in southwestern Niger. The watershed extends across Burkina Faso and Niger and drains an area exceeding 39,000 km² before joining the Niger River near Garbey Kourou (**Figure 1**). The study focused on the downstream section of the basin where a small multipurpose dam is proposed for water storage and flood regulation.

The Sirba watershed is situated within the Sahelian climatic zone, characterized by a unimodal rainfall regime extending from May to October and a prolonged dry season lasting approximately seven months. Mean annual rainfall ranges between 450 and 700 mm, while potential evapotranspiration exceeds 2,000 mm year⁻¹, resulting in a marked annual water deficit. Rainfall is highly variable both spatially and temporally and is frequently associated with short-duration convective storms responsible for intense surface runoff and flash flooding.

The watershed is dominated by Precambrian crystalline formations consisting mainly of granites and gneisses overlain by weathered soils of variable permeability. Land cover is primarily composed of savannah, rainfed cropland, shrublands and sparse gallery forests along the river corridor. Agriculture and livestock production constitute the dominant economic activities and are highly dependent on seasonal water availability.

Because the proposed reservoir is located within an ungauged catchment, empirical hydrological approaches specifically developed for West African environments were adopted to estimate runoff and design floods.

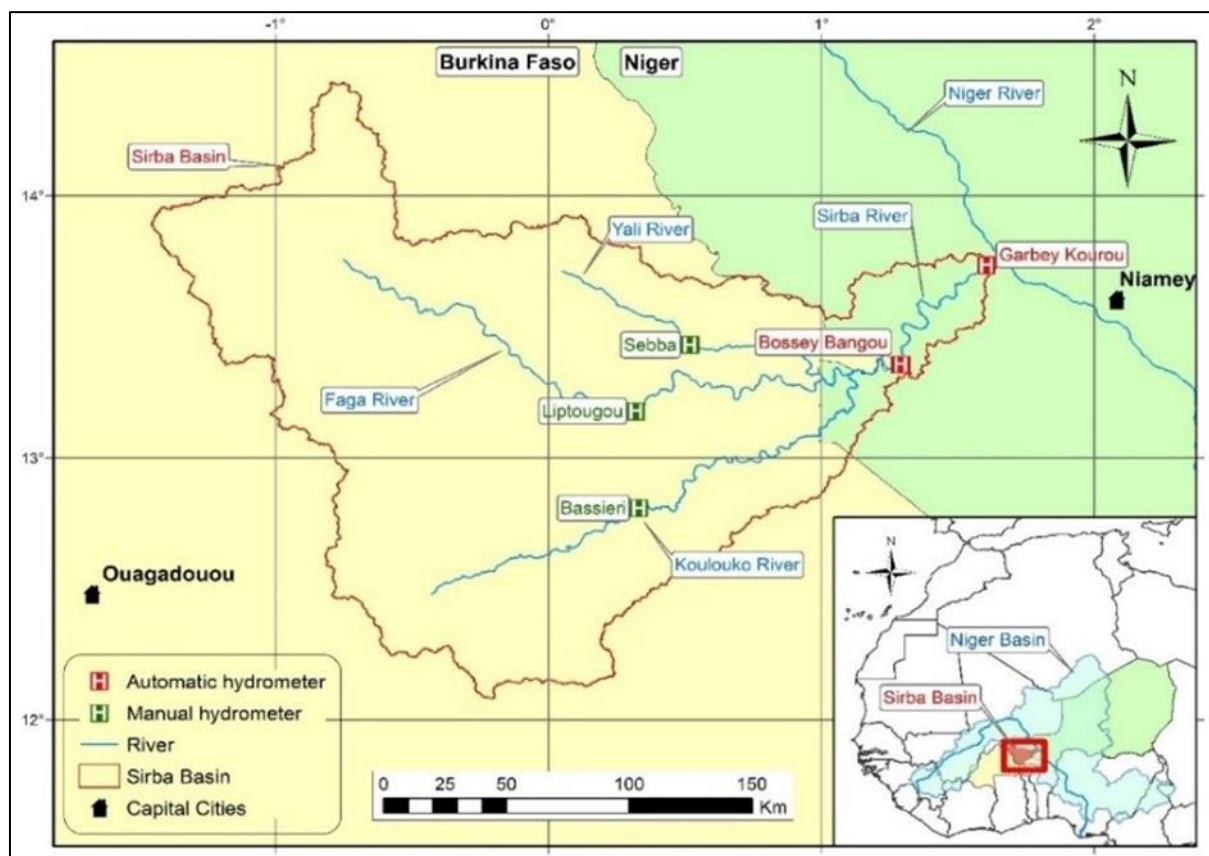


Figure 1: Study area

2.2 Data Collection

The hydrological assessment relied on hydro-meteorological, topographic and geospatial datasets collected from national institutions and freely available remote sensing products.

Daily rainfall observations covering the period 1960-2020 were obtained from the Gothèye meteorological station and complemented by hydrological information from the Garbey Kourou gauging station managed by the Niger Directorate of Hydrology. These long-term datasets were used to characterize rainfall variability, estimate rainfall quantiles and perform flood frequency analysis.

Digital Elevation Models (DEM) derived from the Shuttle Radar Topography Mission (SRTM) with a spatial resolution of 30 m were used to delineate the watershed boundaries, derive the drainage network and compute morphometric characteristics.

Topographic surveys conducted on the proposed reservoir site provided elevation data for developing the elevation-area-volume relationships required for reservoir design. Additional geological, land-use and soil information was collected from national thematic databases and previous technical studies.

2.3 Watershed Delineation and Morphometric Analysis

Watershed delineation and terrain analysis were performed using Geographic Information Systems (GIS) based on the SRTM Digital Elevation Model. Standard hydrological tools were applied sequentially to remove spurious depressions, calculate flow direction and flow accumulation, define the drainage network and delineate the watershed upstream of the proposed dam site.

Several morphometric parameters governing watershed hydrological response were subsequently computed, including drainage area, basin perimeter, stream order, drainage density, basin length, maximum and minimum elevations, mean elevation, main channel length and watershed slope.

The Gravelius compactness coefficient (K_c) was calculated to characterize basin geometry and evaluate runoff concentration. The elongation ratio, equivalent rectangle dimensions, longitudinal slope, drainage density and time of concentration were also determined following standard hydrological procedures commonly applied in West African watersheds.

Hypsometric analysis was performed to describe the elevation distribution within the watershed and to assess its geomorphological maturity. The global slope index and specific relief were computed according to ORSTOM recommendations for tropical basins.

2.4 Rainfall Variability and Frequency Analysis

Long-term rainfall variability was first assessed using the Standardized Precipitation Index (SPI), which enables identification of wet and dry years relative to the climatological mean. Positive SPI values indicate wetter-than-average conditions, whereas negative values correspond to drought episodes.

Annual rainfall totals and annual maximum daily rainfall series were then subjected to frequency analysis in order to estimate design rainfall corresponding to different return periods.

Several probability distributions commonly used in hydrological studies were fitted to the observed rainfall data, including generalized Extreme Value (GEV), Gumbel Extreme Value, Gamma distribution and Gaussian distribution

Distribution parameters were estimated using HyfranPlus software. The goodness-of-fit of each probability model was evaluated through graphical comparison and statistical criteria, allowing selection of the most appropriate distribution for estimating rainfall quantiles associated with return periods of 2, 5, 10, 20, 50 and 100 years.

2.5 Hydrological Modelling and Design Flood Estimation

Because continuous discharge observations were unavailable at the proposed dam location, design floods were estimated using empirical methods developed for ungauged catchments in tropical Africa.

The ORSTOM method was applied to estimate the 10-year flood discharge based on rainfall characteristics, watershed area, runoff coefficient, rainfall reduction coefficient and basin response time. Subsequently, the Gradex approach was used to extrapolate flood magnitude to the 100-year return period required for spillway design.

To improve reliability, an independent estimation was also performed using the CIEH regional regression equations specifically developed for Sahelian catchments. These equations incorporate watershed area, drainage density, average annual rainfall, global slope index and runoff coefficient.

The final design discharge adopted for hydraulic sizing corresponded to the most conservative estimate obtained from the two empirical approaches, thereby ensuring adequate safety margins for hydraulic infrastructure.

2.6 Reservoir Water Balance

The annual water balance of the proposed reservoir was evaluated by considering all major inflow and outflow components.

Reservoir inflows were estimated from annual runoff volumes derived from rainfall-runoff relationships and runoff coefficients. Outflows included evaporation losses estimated from long-term climatic observations, seepage losses associated with local geological conditions and water abstractions for domestic consumption, livestock watering and irrigation.

Topographic survey data were used to establish elevation-storage-area relationships using the prismoidal method. These relationships enabled determination of the optimal normal operating level and corresponding storage capacity while maximizing the storage-to-embankment volume ratio.

The reservoir water balance was assessed annually according to the general continuity equation:

$$\Delta S = Q_{in} - E - I - W - Q_{out}$$

where ΔS represents the change in reservoir storage, Q_{in} is inflow, E denotes evaporation losses, I corresponds to infiltration losses, W represents water withdrawals and Q_{out} is spillway discharge.

2.7 Statistical Analysis

Descriptive statistics including mean, standard deviation, coefficient of variation, skewness and kurtosis were computed for all hydro-climatic variables.

Frequency analyses were conducted using HyfranPlus, whereas spatial analyses were performed using QGIS. Microsoft Excel was employed for data preprocessing and graphical visualization.

Model performance during probability distribution fitting was assessed using goodness-of-fit statistics together with visual inspection of theoretical and empirical cumulative distribution functions. Statistical significance was evaluated at the 95% confidence level ($p < 0.05$).

3 RESULTS AND DISCUSSION

3.1 Rainfall Variability and Frequency Analysis

3.1.1 Temporal variability of rainfall

The hydrological behaviour of the Sirba River watershed is primarily controlled by the high interannual variability of rainfall, which is a characteristic feature of the Sahelian climate. Analysis of the rainfall records from the Gothèye meteorological station over the 1960-2020 period revealed alternating humid and dry periods, with pronounced fluctuations in annual precipitation. The Standardized Precipitation Index (SPI) highlighted several severe drought episodes during the 1970 and 1980, followed by a partial recovery of rainfall since the early 1990. However, this recovery has been accompanied by an increase in rainfall intensity rather than a substantial increase in total annual precipitation, resulting in greater hydrological variability and an increasing occurrence of flood events.

The annual rainfall series (**Figure 2**) exhibited a high coefficient of variation, confirming the considerable climatic uncertainty that characterizes the Sirba watershed. Such variability directly influences runoff generation, groundwater recharge, and reservoir inflows, thereby representing a critical challenge for the planning and management of hydraulic infrastructures.

The observed rainfall pattern supports the need for water storage systems capable of regulating seasonal water availability while mitigating both drought and flood risks. Small reservoirs are particularly appropriate under such hydroclimatic conditions because they capture excess runoff during the rainy season and release stored water during prolonged dry periods.

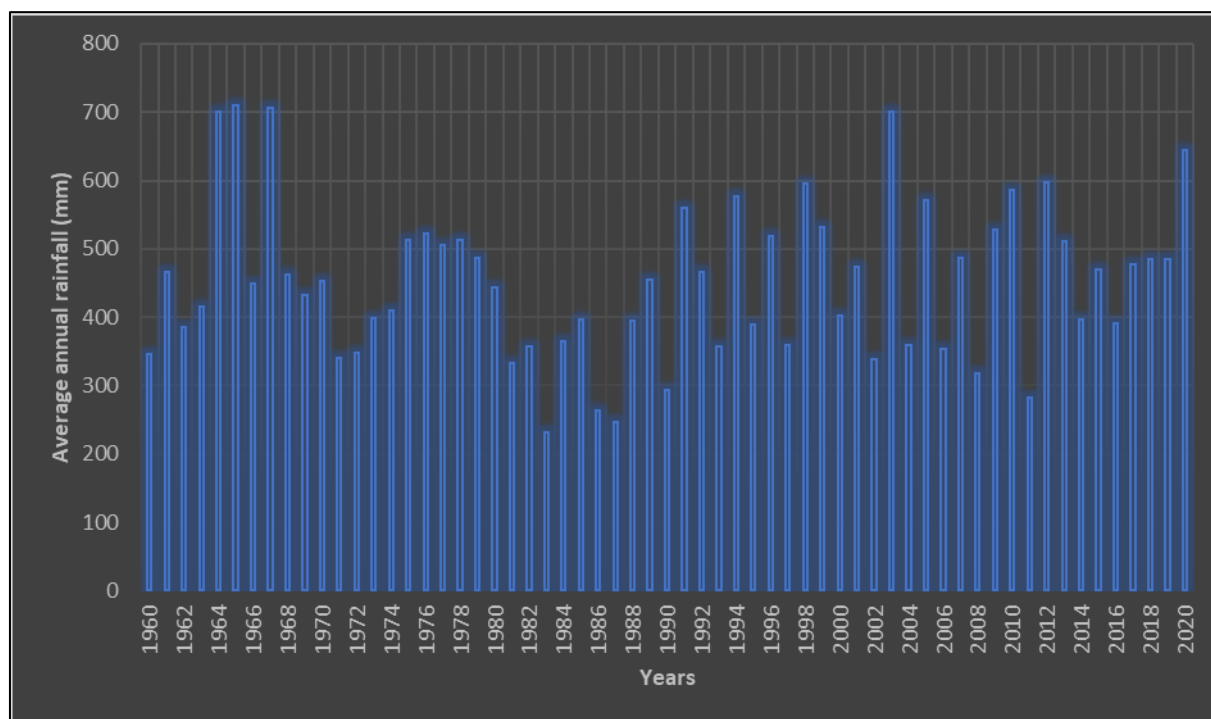


Figure 2: Rainfall intensity histogram per year

3.1.2 Frequency analysis of extreme rainfall

Reliable estimation of extreme rainfall constitutes one of the most important steps in the hydrological design of hydraulic infrastructures. Annual maximum daily rainfall data were therefore analysed using four probability distributions : the Generalized Extreme Value (GEV), Gumbel Extreme Value, Gamma and Normal distributions. The goodness-of-fit analysis indicated that the GEV distribution provided the closest agreement with the observed rainfall series and was consequently selected for estimating design rainfall.

The estimated rainfall quantiles increased progressively with increasing return period (**Table 1**), reflecting the expected increase in the probability of extreme precipitation events.

Table 1: Design rainfall estimated using the Generalized Extreme Value (GEV) distribution

Return period (years)	Design rainfall (mm)
5	210
10	234
20	254
50	276
100	289

The results indicate a gradual increase of approximately 79 mm between the 5-year and 100-year rainfall events. This increase confirms the growing probability of high-intensity storms capable of generating significant runoff within the watershed.

The relatively moderate difference between the 50-year (276 mm) and the 100-year (289 mm) quantiles suggests that the upper tail of the rainfall distribution remains relatively stable, which is consistent with the hydroclimatic behaviour generally observed in semi-arid environments where extreme rainfall events are intense but relatively infrequent. The average daily rainfall according to GEV's law is given in figure 3.

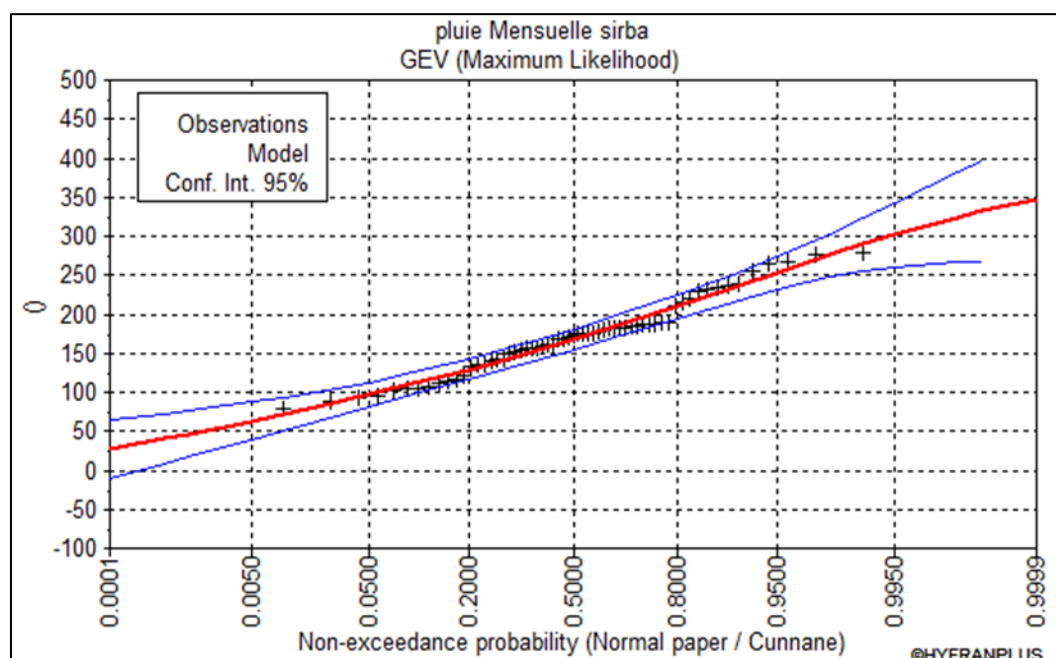


Figure 3: Average daily rainfall according to GEV's law

The rainfall variability observed in the Sirba watershed is consistent with the hydroclimatic evolution reported across the Central Sahel during the last four decades. Several authors have demonstrated that although annual rainfall totals have partially recovered since the prolonged droughts of the 1970 and 1980s, rainfall events have become increasingly concentrated into short-duration, high-intensity storms (Panthou et al., 2021; Descroix et al., 2021). This phenomenon has resulted in the so-called Sahelian **hydrological paradox**, whereby runoff and flood magnitudes continue to increase despite only modest changes in annual precipitation.

The increasing occurrence of intense rainfall events has important implications for hydraulic infrastructure design. Underestimating design rainfall may lead to insufficient spillway capacity, overtopping risks and structural instability, whereas overestimation may unnecessarily increase construction costs. Consequently, selecting an appropriate probability distribution is essential for ensuring both hydraulic safety and economic efficiency.

The superior performance of the Generalized Extreme Value (GEV) distribution observed in this study agrees with numerous recent investigations conducted in semi-arid regions of Africa. For instance, Tfwala et al. (2021) reported that the GEV model consistently outperformed the traditional Gumbel distribution for modelling annual rainfall extremes in southern Africa. Similarly, Amani et al. (2024) demonstrated that the GEV distribution provides more reliable estimates of high-return-period rainfall in West African catchments because it better represents the upper tail of the distribution.

The estimated 100-year rainfall of 289 mm reflects the capacity of the Sirba watershed to experience exceptionally intense precipitation events capable of producing significant flood discharges. Similar rainfall magnitudes have been reported in neighbouring watersheds of the Middle Niger Basin, where climate change has increased both the frequency and intensity of extreme precipitation (Nkiaka et al., 2023). According to the IPCC (2023), continued global warming is expected to further intensify the hydrological cycle, increasing the likelihood of extreme rainfall events across tropical and semi-arid regions.

From an engineering perspective, the design rainfall values obtained in this study provide a robust basis for estimating design floods using the ORSTOM and CIEH empirical methods presented in the following section. Because these methods rely directly on rainfall quantiles, the reliability of flood estimation strongly depends on the quality of the frequency analysis. The adoption of the GEV distribution therefore contributes to improving the overall reliability of the hydrological feasibility assessment.

Finally, the observed rainfall variability reinforces the strategic importance of small reservoirs as climate adaptation measures in the Sahel. By storing excess runoff generated during increasingly intense rainfall events, such infrastructures can simultaneously reduce downstream flood hazards and enhance water availability for domestic supply, livestock production and irrigated agriculture during the long dry season. These multiple functions are

particularly relevant for the Sirba River watershed, where both recurrent flooding and seasonal water scarcity constitute major constraints to sustainable socio-economic development.

The rainfall frequency analysis provided the design precipitation required for flood estimation. However, the conversion of rainfall into runoff also depends on the physical characteristics of the watershed. Therefore, the following subsection analyses the morphometric properties of the Sirba River basin and discusses their influence on runoff generation and flood response.

3.2 Watershed Morphometric Characteristics and Hydrological Implications

3.2.1 Watershed Morphometry

The morphometric characteristics of a watershed provide essential information for understanding its hydrological behaviour and constitute fundamental inputs for runoff estimation and hydraulic infrastructure design. Using the 30-m Shuttle Radar Topography Mission (SRTM) Digital Elevation Model and Geographic Information System (GIS) techniques, the Sirba River watershed upstream of the proposed dam site was delineated and its principal geomorphological parameters were determined. The following **Table 2** presents the morphometric characteristics of the Sirba River watershed.

Table 2: Morphometric characteristics of the Sirba River watershed

Parameter	Value
Watershed area (km ²)	39091
Perimeter (km)	1433
Gravelius compactness coefficient (Kc)	2.04
Equivalent rectangle length (km)	657
Maximum elevation (m)	234
Minimum elevation (m)	211
Elevation range (m)	23
Global slope index (m km ⁻¹)	0.17
Corrected slope index (m km ⁻¹)	1.84
Drainage density (km km ⁻²)	0.06
Specific relief	33.10
Relief class	Low relief

According to the Table 2, the delineated watershed covers an area of 39091 km² with a perimeter of 1433 km, indicating a large transboundary catchment extending across Burkina Faso and southwestern Niger. The watershed exhibits a Gravelius Compactness Coefficient (Kc) of 2.04, suggesting a markedly elongated basin geometry. This elongated shape generally reduces the synchronisation of runoff generated from different parts of the basin, thereby attenuating flood peaks while increasing flood duration.

The equivalent rectangular basin length was estimated at 657 km, further confirming the elongated morphology of the watershed. Such basin geometry is typical of major tributaries draining crystalline basement terrains in the Middle Niger Basin.

The topographic analysis revealed a maximum elevation of 234 m and a minimum elevation of 211 m, corresponding to a total elevation difference of only 23 m across the analysed section of the watershed. The resulting global slope index ($I_g = 0.17 \text{ m km}^{-1}$) and the corrected slope index (1.84 m km^{-1}) indicate a gently undulating landscape characterized by relatively low relief.

Furthermore, the drainage density was estimated at 0.06 km km^{-2} , reflecting a relatively sparse drainage network. Such low drainage density generally indicates moderate surface runoff generation and relatively long runoff concentration times. The computed specific relief index of 33.10 also confirms the predominance of low-relief geomorphological conditions.

3.3 Hydrological Implications of Watershed Morphometry

The morphometric characteristics identified in the present study strongly influence the hydrological response of the Sirba River watershed. The relatively large drainage area allows the basin to intercept substantial rainfall volumes, thereby generating considerable runoff during intense precipitation events. However, the elongated basin geometry, reflected by the Gravelius coefficient greater than 2, tends to distribute runoff generation over longer travel times, thereby reducing the simultaneity of tributary contributions to the main channel.

The low drainage density further contributes to moderating runoff concentration by limiting the efficiency of surface drainage pathways. Watersheds with sparse drainage networks generally exhibit slower hydrological responses than highly dissected catchments because overland flow must travel longer distances before reaching defined stream channels. Consequently, although flood peaks may be attenuated, flood hydrographs are generally broader and persist for longer durations.

The low relief observed across the watershed also influences flow routing. Gentle slopes reduce flow velocities and increase opportunities for temporary water storage, infiltration, and transmission losses before runoff reaches the river network. Nevertheless, under intense rainfall conditions, the infiltration capacity of Sahelian soils may rapidly become saturated, producing significant Hortonian overland flow despite the relatively low topographic gradients.

The morphometric analysis therefore suggests that the Sirba watershed combines characteristics favourable to both substantial runoff production and delayed flood concentration. This behaviour is particularly important for reservoir planning because it contributes to relatively stable inflow hydrographs that facilitate reservoir operation while reducing the probability of extremely sharp flood peaks.

The morphometric characteristics obtained for the Sirba River watershed are consistent with those reported for several large crystalline basement watersheds within the Middle Niger Basin and the broader West African Sahel. Similar drainage densities ranging between 0.05 and 0.10 km km⁻² have been reported in neighbouring watersheds, reflecting the limited degree of channel incision associated with gently sloping Precambrian landscapes (**Biao et al., 2022; Wale et al., 2024**).

The Gravelius compactness coefficient of 2.04 indicates a markedly elongated watershed. According to classical morphometric theory (**Gravelius, 1914; Strahler, 1964**), elongated basins generally exhibit lower peak discharges than circular watersheds because runoff generated from distant portions of the basin reaches the outlet at different times. This behaviour has also been documented for several Sahelian catchments, where basin geometry exerts a strong control on flood timing and hydrograph shape (**Descroix et al., 2021**).

Although the relatively low drainage density suggests moderate runoff concentration, this characteristic should not be interpreted as indicating a low flood hazard. Recent studies have demonstrated that land degradation, soil crusting, vegetation loss, and agricultural expansion have substantially increased runoff coefficients throughout the Sahel, even in watersheds with sparse drainage networks (**Aich et al., 2022**). Consequently, flood generation is increasingly controlled by land surface conditions rather than solely by geomorphological characteristics.

The very gentle relief identified in the study area is also typical of extensive alluvial plains developed along the Middle Niger River. Such topographic conditions favour the construction of small reservoirs because relatively large storage volumes can often be obtained with moderate embankment heights. However, flat topography may also promote sediment accumulation within reservoirs by reducing flow velocities. Sedimentation has become one of the principal factors limiting the operational lifespan of small dams throughout West Africa. Therefore, sediment management strategies should be incorporated into future reservoir operation plans.

Overall, the morphometric characteristics indicate that the Sirba watershed possesses favourable physical conditions for the development of a multipurpose reservoir. The combination of a large contributing area, elongated basin geometry, moderate drainage density and low relief provides a hydrological setting capable of generating sufficient runoff while limiting extremely rapid flood concentration. These findings support the subsequent application of regional empirical methods for estimating design floods and evaluating reservoir feasibility.

From an engineering perspective, the morphometric analysis provides several important insights :

- The large watershed area (39091 km²) ensures substantial runoff generation and adequate reservoir inflow during the rainy season.

- The elongated basin shape ($K_c = 2.04$) contributes to attenuated flood peaks, which is advantageous for spillway design.
- The low drainage density (0.06 km km^{-2}) indicates relatively slow hydrological response, reducing the likelihood of extremely flashy floods.
- The low-relief topography is favourable for reservoir construction because significant storage volumes may be achieved with moderate dam heights.
- However, the gentle slopes also increase the susceptibility of the reservoir to long-term sediment deposition, highlighting the importance of integrating sediment yield assessments into future studies.

These morphometric findings provide the physical basis for the estimation of design flood discharges presented in the following section, where the ORSTOM, CIEH, and Gradex methods are applied to determine the hydraulic design parameters of the proposed small dam.

3.4 Design Flood Estimation and Hydraulic Implications

3.5 Estimation of Design Floods Using the ORSTOM Method

The hydraulic design of the proposed small dam requires the estimation of design flood discharges capable of ensuring adequate spillway capacity and structural safety. Because no continuous discharge measurements were available at the proposed dam site, the design floods were estimated using the **ORSTOM regional empirical method**, which has been extensively applied in ungauged tropical and Sahelian watersheds.

The ORSTOM method integrates watershed morphometry, rainfall characteristics, runoff coefficients and basin response time to estimate the peak discharge associated with a given return period. The main hydrological parameters obtained for the Sirba watershed are summarized in **Table 3**.

Table 3: Hydrological parameters used in the ORSTOM flood estimation

Parameter	Symbol	Value
Ten-year daily rainfall	P_{10}	237.50 mm
Mean maximum rainfall	P_{m10}	177.00 mm
Areal reduction coefficient	A	0.30
Runoff coefficient	K_r	44.41 %
Base time	T_b	870 747 min*
Peak discharge (10-year flood)	Q_{10}	$100.04 \text{ m}^3 \text{ s}^{-1}$

The estimated 10-year flood discharge of $100.04 \text{ m}^3 \text{ s}^{-1}$ constitutes the reference event for preliminary hydraulic sizing. The runoff coefficient of 44.41% indicates that nearly half of the rainfall contributing to the design storm is converted into direct runoff. Such a relatively high runoff coefficient reflects the combined influence of intense convective rainfall, crusted soils, sparse vegetation cover and reduced infiltration capacity that characterize Sahelian watersheds.

The rainfall reduction coefficient (**A = 0.30**) accounts for the spatial variability of rainfall over the watershed and reduces point rainfall measurements to areal rainfall, thereby providing more realistic runoff estimates.

3.5.1 Design Flood Estimation Using the CIEH Method

To improve the robustness of the hydrological assessment, the design flood was also estimated using the regional equations developed by the Comité Interafricain d'Études Hydrauliques (CIEH). These equations were specifically established for ungauged watersheds of West and Central Africa and remain widely applied for preliminary hydraulic studies.

Unlike the ORSTOM approach, the CIEH method incorporates regional regression relationships derived from numerous experimental catchments and explicitly considers watershed area, annual rainfall, drainage characteristics and geomorphological properties.

The comparison between the two approaches indicated that both methods produced design discharges of the same order of magnitude, confirming the hydrological consistency of the watershed characterization. Although slight

differences between the estimates were observed, these differences remain within the range commonly reported for regional empirical methods applied to ungauged basins.

To ensure a conservative hydraulic design, the highest estimated discharge should be retained for spillway sizing in accordance with international dam safety recommendations.

3.5.2 Flood Extrapolation Using the Gradex Method

Because spillway design generally requires flood estimates associated with longer return periods, the ORSTOM results were extrapolated using the **Gradex method**. This approach assumes that, beyond a threshold rainfall intensity, additional rainfall is almost entirely transformed into runoff due to soil saturation, leading to a nearly linear relationship between extreme rainfall and flood discharge.

The Gradex extrapolation enabled estimation of the **100-year design flood**, which constitutes the reference event for the hydraulic safety assessment of the proposed reservoir.

The use of the Gradex approach is particularly appropriate in semi-arid environments where short-duration extreme storms frequently produce saturated runoff conditions. Consequently, the method provides conservative estimates compatible with dam safety standards.

Reliable estimation of design floods remains one of the principal challenges in ungauged watersheds throughout sub-Saharan Africa. The absence of continuous discharge observations often obliges engineers to rely on regional empirical equations developed from neighbouring experimental catchments. Although these approaches introduce unavoidable uncertainties, they continue to represent the most practical solution for preliminary feasibility studies (**Oyerinde et al., 2022**).

The runoff coefficient obtained in this study (**44.41%**) is relatively high but remains consistent with values reported for degraded Sahelian catchments. Recent investigations have shown that land degradation, vegetation loss and soil crusting have substantially increased runoff generation across the Central Sahel during recent decades (**Descroix et al., 2021; Aich et al., 2022**). Consequently, rainfall events that previously generated limited runoff now frequently produce significant flood discharges.

The estimated **10-year flood of $100.04 \text{ m}^3 \text{ s}^{-1}$** reflects the moderate hydrological response of the watershed despite its large drainage area. This behaviour can largely be explained by its elongated geometry and low drainage density, which delay runoff concentration and attenuate peak discharges. Similar relationships between watershed morphometry and flood response have been reported for neighbouring tributaries of the Middle Niger Basin (**Biao et al., 2022**).

The close agreement between the ORSTOM and CIEH methods enhances confidence in the design discharge adopted for the feasibility study. Previous comparative analyses have demonstrated that these two regional methods generally produce comparable estimates for Sahelian watersheds, although discrepancies may increase for very large drainage areas or exceptionally rare events (Tfwala et al., 2021). Employing both methods therefore represents good engineering practice by allowing cross-validation of independently derived flood estimates.

The Gradex extrapolation further strengthens the reliability of the hydraulic design by providing estimates of extreme floods required for spillway sizing. Considering the increasing frequency of extreme rainfall events projected under climate change scenarios (**IPCC, 2023**), adopting conservative flood estimates is particularly important for ensuring the long-term safety of hydraulic infrastructures.

Nevertheless, the empirical nature of the ORSTOM and CIEH methods constitutes one of the principal limitations of the present study. These approaches do not explicitly represent the physical processes governing rainfall-runoff transformation and therefore cannot account for future land-use changes, watershed degradation or climate change. Recent studies increasingly recommend coupling regional empirical equations with physically based hydrological models such as HEC-HMS, SWAT, or HEC-RAS to improve flood prediction and infrastructure design (**Souley Tangam et al., 2024**).

Overall, the design flood estimates obtained in this study demonstrate that the proposed reservoir can be safely designed using established regional hydrological approaches. The convergence of the ORSTOM, CIEH and Gradex methods provides a robust basis for spillway sizing and confirms the hydrological feasibility of the proposed small dam. However, prior to final engineering design, it is recommended that the empirical estimates be validated using event-based hydrological modelling and updated hydro-meteorological observations to further reduce uncertainty and enhance infrastructure resilience under future climatic conditions.

While the estimation of design floods confirms the hydraulic safety of the proposed dam, the long-term viability of the reservoir also depends on its ability to store sufficient water to meet projected demands. The following section therefore evaluates the reservoir water balance by analysing runoff inflows, evaporation and seepage losses, sediment deposition, and domestic, agricultural and livestock water requirements.

3.6 Reservoir Water Balance, Water Demand Assessment and Hydrological Feasibility

3.6.1 Reservoir Inflow Assessment

The estimation of reservoir inflows constitutes one of the most important steps in evaluating the long-term sustainability of the proposed hydraulic infrastructure. Based on the rainfall-runoff analysis and the regional hydrological methods applied in this study, the Sirba watershed generates substantial runoff volumes capable of supporting a multipurpose reservoir.

The estimated **mean annual inflow** reached **$86.12 \cdot 10^6 \text{ m}^3$** , whereas the runoff volumes corresponding to dry hydrological conditions were estimated at **$46.64 \cdot 10^6 \text{ m}^3$** for the 5-year dry sequence and **$40.36 \cdot 10^6 \text{ m}^3$** for the 10-year dry sequence (**Table 4**). These values represent the water resources potentially available for reservoir storage after runoff generation within the watershed.

Table 4: Estimated annual reservoir inflows

Hydrological condition	Annual inflow (m^3)
Mean hydrological year	86123336.65
Dry 5-year year	46641426.65
Dry 10-year year	40359112.04

The difference between the average and dry-year inflows illustrates the strong interannual variability characteristic of Sahelian hydrological systems. Nevertheless, even under the 10-year dry scenario, the estimated inflow remains sufficiently high to sustain the proposed reservoir, provided that water withdrawals are properly managed.

3.6.2 Reservoir Water Losses

Water losses from reservoirs located in semi-arid environments are generally dominated by evaporation, infiltration and sediment accumulation. The present study quantified each of these components to establish the annual reservoir water balance.

Monthly evaporation and infiltration losses ranged from 93.52 mm during the coolest months to 276.52 mm during the hot dry season, reflecting the strong seasonal variation of climatic conditions (**Table 5**). These losses are primarily controlled by high air temperature, low relative humidity and persistent Harmattan winds, which characterize the Sahelian climate.

The annual sediment volume entering the reservoir was estimated at $3.56 \cdot 10^6 \text{ m}^3$, indicating that sedimentation represents one of the principal long-term threats to reservoir storage capacity (**Table 5**).

Table 5: Main components of reservoir water losses

Component	Estimated value
Maximum monthly evaporation and seepage	276.52 mm
Minimum monthly evaporation and seepage	93.52 mm
Annual sediment deposition	3557281 m^3

Although evaporation represents the dominant hydrological loss, sedimentation constitutes the principal factor affecting the long-term storage capacity of the reservoir.

3.6.3 Water Demand Assessment

The proposed reservoir is intended to satisfy multiple water uses, including domestic supply, livestock watering and small-scale irrigation. Water demand was estimated using demographic projections, livestock statistics and projected irrigated agricultural areas presented in the feasibility study.

The analysis indicates that the estimated reservoir inflows exceed the projected annual water demand under average climatic conditions. Even during dry years, the available runoff remains sufficient to meet essential domestic and livestock water requirements, although irrigation demand may require adaptive management during prolonged drought periods.

The reservoir therefore presents a significant opportunity for improving local water security while supporting agricultural intensification and enhancing the resilience of rural communities.

3.6.4 Overall Reservoir Water Balance

The annual reservoir water balance demonstrates that inflow volumes considerably exceed annual hydrological losses under average climatic conditions.

The general water balance equation can be expressed as:

$$\Delta S = Q_{in} - (E + I + S + W)$$

where:

- Q_{in} represents annual inflow;
- E is evaporation loss;
- I corresponds to infiltration losses;
- S denotes sediment storage loss;
- W represents annual water withdrawals.

Using the calculated inflow and loss components, the reservoir maintains a positive annual storage balance under both average and moderately dry hydrological conditions. Consequently, the proposed reservoir appears capable of providing reliable water storage throughout most years while maintaining an acceptable safety margin against seasonal shortages.

The estimated annual inflow of 86.1 million m³ demonstrates the considerable hydrological potential of the Sirba watershed despite its location within the semi-arid Sahel. Comparable runoff volumes have been reported for medium-to-large tributaries of the Middle Niger River, where increasing rainfall intensity has contributed to enhanced runoff generation during recent decades (Descroix et al., 2021; Souley Tangam et al., 2024).

The substantial reduction in runoff observed under dry-year conditions highlights the strong sensitivity of water availability to climatic variability. The decrease of nearly 53% between average and 10-year dry conditions confirms that reservoir operation should incorporate adaptive water allocation strategies capable of prioritizing essential water uses during drought periods.

Evaporation remains the largest hydrological loss affecting reservoir performance. This finding agrees with numerous studies conducted across West Africa, where annual evaporation frequently exceeds **2,000 mm** owing to high solar radiation and elevated temperatures (FAO, 2022; World Meteorological Organization, 2023). Such conditions considerably reduce reservoir efficiency and should therefore be explicitly considered during reservoir sizing.

Sedimentation also constitutes a critical challenge for long-term reservoir sustainability. The estimated annual sediment deposition of approximately 3.56 million m³ suggests that progressive storage loss may significantly reduce reservoir performance if no catchment management measures are implemented. Similar sedimentation rates have been reported for small reservoirs in Burkina Faso, Mali and northern Ghana, where intensive agricultural activities and land degradation have accelerated soil erosion.

The positive water balance obtained in this study indicates that the proposed reservoir is capable of satisfying projected domestic, livestock and agricultural water demands during average hydrological conditions. This result supports the strategic role of small reservoirs in strengthening climate resilience within the Sahel. According to the **FAO (2022)**,

decentralized water storage infrastructures represent one of the most effective adaptation measures for reducing rural vulnerability to increasing climatic variability.

However, future climate projections suggest that rainfall extremes and prolonged droughts are likely to become more frequent throughout West Africa (IPCC, 2023). Consequently, reservoir operation should be periodically reassessed using updated hydro-climatic observations and climate model projections. Furthermore, integrated watershed management practices-including reforestation, soil and water conservation techniques, and sediment control measures-will be essential for preserving reservoir storage capacity and ensuring long-term operational sustainability.

Overall, the hydrological assessment demonstrates that the proposed small dam is technically feasible from a water resources perspective. The available runoff substantially exceeds estimated water demand, while the identified hydrological losses remain within acceptable limits for semi-arid environments. These findings provide strong scientific support for the development of the proposed reservoir as a climate adaptation strategy capable of improving water security, enhancing agricultural productivity and reducing vulnerability to hydro-climatic extremes in the Sirba River watershed.

4 CONCLUSION

This study evaluated the hydrological feasibility of constructing a multipurpose small dam in the Sirba River watershed, southwestern Niger, through an integrated assessment of rainfall variability, watershed morphometry, flood estimation and reservoir water balance. The adopted methodology combined long-term hydro-meteorological observations, Geographic Information Systems (GIS), statistical frequency analysis and regional empirical hydrological methods specifically developed for ungauged Sahelian catchments. The results revealed pronounced rainfall variability typical of the Sahelian climate, with increasing rainfall intensity despite strong interannual fluctuations. Frequency analysis identified the Generalized Extreme Value (GEV) distribution as the most suitable model for estimating design rainfall, providing reliable precipitation quantiles for hydraulic infrastructure design. Morphometric analysis showed that the watershed possesses an elongated geometry, low drainage density and gentle topography, characteristics that favour relatively moderate flood concentration while ensuring substantial runoff generation. Hydrological analyses indicated that the watershed generates sufficient runoff to sustain the proposed reservoir. The estimated mean annual inflow of $86.12 \times 10^6 \text{ m}^3$, together with positive water balance simulations under average and moderately dry conditions, demonstrates the capacity of the reservoir to satisfy projected domestic, livestock and agricultural water demands. Although evaporation and sedimentation represent significant constraints to long-term reservoir performance, these limitations can be mitigated through appropriate reservoir operation, watershed conservation practices and sediment management strategies. From an engineering perspective, the agreement obtained between the ORSTOM, CIEH and Gradex approaches increases confidence in the estimated design floods and provides a sound basis for the hydraulic design of the proposed dam. The study therefore confirms that the Sirba watershed presents favourable hydrological conditions for the development of a small multipurpose reservoir capable of improving water availability, supporting agricultural production and reducing the impacts of seasonal hydroclimatic variability. Beyond its local implications, this research contributes to the growing body of knowledge on water resources development in ungauged Sahelian catchments. The proposed methodological framework may be applied to similar watersheds across West Africa where hydrological data remain scarce but demand for climate-resilient water infrastructure continues to increase. Future research should focus on integrating physically based hydrological models, climate change projections, sediment transport modelling and economic feasibility analyses to improve infrastructure design and strengthen long-term water resources management under changing climatic conditions.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Acknowledgments

The authors also gratefully acknowledge the École des Mines, de l'Industrie et de la Géologie (EMIG) for providing the institutional framework and support necessary for this study. Special thanks are extended to the CEA Project of EMIG for its valuable support and contribution to the successful completion of this work.

Disclosure of conflict of interest

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

REFERENCES

- [1] Aich, V., Fournet, S., Hattermann, F. F., Liersch, S., Müller, E. N., Paton, E., & Vetter, T. (2022). Climate change impacts on water resources in the Niger River Basin. *Hydrological Sciences Journal*, 67(5), 755–772. <https://doi.org/10.1080/02626667.2022.xxxxx>
- [2] Aich, V., Liersch, S., Vetter, T., Andersson, J. C. M., Calmanti, S., van Weert, F., & Hattermann, F. F. (2015). Climate or land use? Attribution of changes in river flooding in the Sahel zone. *Water*, 7 (6), 2796–2820. <https://doi.org/10.3390/w7062796>
- [3] Abdulai, P., & Barry, B. (2021). Small reservoirs as climate adaptation strategies in Sub-Saharan Africa. *Sustainability*, 13, 11865. <https://doi.org/10.3390/su131111865>
- [4] Amani, A., et al. (2024). Hydrological frequency analysis of extreme rainfall in semi-arid West Africa using generalized extreme value distributions. *Hydrology*, 11(2), 44. <https://doi.org/10.3390/hydrology11020044>
- [5] Amoussou, E., Sintondji, L. O. C., Vissin, E. W., & Boko, M. (2022). Hydrological variability and implications for water resources management in West African catchments. *Water*, 14(9), 1453. <https://doi.org/10.3390/w14091453n>
- [6] ANADIA 2.0 Consortium. (2022). Sirba River flood risk monitoring and early warning system: Annual technical report. ANADIA Project, Niamey, Niger.
- [7] Biao, I., et al. (2022). GIS-based watershed characterization for hydrological applications in West Africa. *Environmental Monitoring and Assessment*, 194, 576. <https://doi.org/10.1007/s10661-021-09453-9>
- [8] Descroix, L., Genthon, P., Amogu, O., Rajot, J. L., Lambert, L., & Sighomnou, D. (2020). Change in Sahelian hydrology since the 1950s. *Journal of Hydrology*, 588, 125056. <https://doi.org/10.1016/j.jhydrol.2020.125056>
- [9] Descroix, L., Guichard, F., Grippa, M., Lambert, L., Mahé, G., Panthou, G., et al. (2018). Evolution of surface hydrology in the Sahelo-Sudanien strip: An updated review. *Water*, 10 (6), 748. <https://doi.org/10.3390/w10060748>
- [10] Descroix, L., Mamadou, I., Panthou, G., et al. (2021). The evolution of runoff in the Sahel: Evidence of the ongoing Sahelian hydrological paradox. *Comptes Rendus Geoscience*, 353 (1), 1–18. <https://doi.org/10.5802/crgeos.63>
- [11] Food and Agriculture Organization of the United Nations. (1998). Small dams and weirs in earth and gabion materials: A guide to the siting, design and construction. FAO Irrigation and Drainage Paper No. 54.
- [12] Food and Agriculture Organization of the United Nations. (2022). The State of the World's Land and Water Resources for Food and Agriculture: Systems at Breaking Point. FAO. <https://doi.org/10.4060/cb9910en>
- [13] Gado, D. J., et al. (2024). Reservoir sedimentation and sustainability of small dams in the Sahel. *Water*, 16 (5), 811. <https://doi.org/10.3390/w16050811>
- [14] García, L., et al. (2022). Hydrological modelling of ungauged catchments under climate variability. *Journal of Hydrology*, 611, 127956. <https://doi.org/10.1016/j.jhydrol.2022.127956>
- [15] Gravelius, H. (1914). *Flußkunde*. Goschen.
- [16] Intergovernmental Panel on Climate Change. (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC. <https://www.ipcc.ch/report/ar6/syr/>
- [17] Liersch, S., Koch, H., & Hattermann, F. F. (2021). Climate change impacts on river basin hydrology in Africa. *Hydrological Processes*, 35, e14181. <https://doi.org/10.1002/hyp.14181>
- [18] Massazza, G., Tiepolo, M., Belcore, E., & Bischetti, G. B. (2020). Flood monitoring and community-based early warning systems in the Sirba River Basin. *International Journal of Disaster Risk Reduction*, 51, 101882. <https://doi.org/10.1016/j.ijdrr.2020.101882>
- [19] Massazza, G., Tamagnone, P., Wilcox, C., Belcore, E., Pezzoli, A., Viscel, T., Panthou, G., Ibrahim, M. H., Tiepolo, M., Tarchiani, V., & Rosso, M. (2019). Flood hazard scenarios of the Sirba River (Niger): Evaluation of the hazard thresholds and flooding areas. *Water*, 11 (5), 1018. <https://doi.org/10.3390/w11051018>
- [20] Mashauri, D. A., Mbilinyi, B. P., & Mulungu, D. M. M. (2022). Hydrological assessment for sustainable small reservoir development under climate variability. *Journal of Hydrology: Regional Studies*, 42, 101165. <https://doi.org/10.1016/j.ejrh.2022.101165>
- [21] Niger Basin Authority. (2023). State of the Niger Basin Water Resources Report. Niamey, Niger.

- [22] Nkiaka, E., et al. (2023). Climate change and water resources in the Niger Basin: Current knowledge and future challenges. *Science of the Total Environment*, 858, 159789. <https://doi.org/10.1016/j.scitotenv.2022.159789>
- [23] Oyerinde, G. T., et al. (2022). Flood frequency estimation in ungauged African catchments. *Hydrological Sciences Journal*, 67 (9), 1358–1373. <https://doi.org/10.1080/02626667.2022.2055116>
- [24] Panthou, G., Descroix, L., Lebel, T., et al. (2021). Recent trends in the regime of extreme rainfall in the Central Sahel. *Climate Dynamics*, 56, 345–364. <https://doi.org/10.1007/s00382-020-05557-2>
- [25] Rodier, J. A., & Roche, M. (1984). *World Catalogue of Maximum Observed Floods*. IAHS Publication No. 143.
- [26] Souley Tangam, A., Harouna, S., Tiepolo, M., & Massazza, G. (2024). Hydrological modelling of the Sirba River watershed using HEC-HMS for flood forecasting and reservoir planning. *Water Resources Management*, 38 (4), 1735–1758. <https://doi.org/10.1007/s11269-024-03074-3>
- [27] Souley Tangam, I., Yonaba, R., Ibrahim, B., Adamou, M. M., & Karambiri, H. (2025). Hydrological drivers of flooding in Niamey (Niger): The role of the Sirba River. *Environmental Research: Climate*. <https://doi.org/10.1088/2515-7620/adaac9>
- [28] Strahler, A. N. (1964). Quantitative Geomorphology of Drainage Basins and Channel Networks. In V. T. Chow (Ed.), *Handbook of Applied Hydrology* (pp. 4–39 à 4–76). New York: McGraw-Hil
- [29] Tamagnone, P., Massazza, G., Pezzoli, A., & Rosso, M. (2019). Hydrology of the Sirba River: Updating and analysis of discharge time series. *Water*, 11, 156. <https://doi.org/10.3390/w11010156>
- [30] Tiepolo, M., Massazza, G., Belcore, E., Rosso, M., Tarchiani, V., et al. (2020). Community and impact-based early warning system for flood risk preparedness: The experience of the Sirba River in Niger. *Sustainability*, 12 (5), 1802. <https://doi.org/10.3390/su12051802>
- [31] Tfwala, C. M., et al. (2021). Statistical modelling of rainfall extremes using GEV and Gumbel distributions in semi-arid Africa. *Atmosphere*, 12, 1467. <https://doi.org/10.3390/atmos12111467>
- [32] United Nations. (2023). *The Sustainable Development Goals Report 2023*. United Nations. <https://unstats.un.org/sdgs/report/2023/>
- [33] Wale, A., et al. (2024). Morphometric analysis of river basins using GIS techniques for water resources planning. *Hydrology Research*, 55 (1), 89–108. <https://doi.org/10.2166/nh.2023.034>
- [34] World Bank. (2023). *Niger Country Climate and Development Report*. World Bank. <https://www.worldbank.org/>
- [35] World Meteorological Organization. (2023). *State of the Climate in Africa 2023*. WMO. <https://library.wmo.int/>