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Evaluating and Mitigating Environmental Effects of Hydroelectric Dams: A Case Study from Cameroon

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Abstract

Cameroon's energy security hangs precariously in the balance as accelerated hydroelectric dam development becomes a vital strategic lever nationwide suddenly. This dynamic has frequently been woefully underestimated in terms of environmental fallout resulting in considerable ecological degradation of river basins worldwide. A systemic quantitative analysis examining effects caused mainly by national hydroelectric infrastructures is proposed in this present study. A multidisciplinary approach melding spatial remote sensing ecotoxicological assessments and hydrosedimentary modelling achieves this through various intricate means. Major transformations occur upstream and downstream of dams within aquatic ecosystems and terrestrial ones exhibiting biodiversity degradation severely. Results indicate a reduction exceeding 40% in sediment flows naturally and significant loss of wetlands alongside critical alterations in fish species reproductive dynamics. Integrated adaptive management strategies have been formulated in response to such a humongous challenge pretty quickly nowadays. Ecological spillways are established and biological corridors restored whilst optimisation of water regimes occurs based on various ecological flow models. Originality of this research lies in development of contextualised methodological framework that combines advanced environmental modelling with energy governance pretty seamlessly. A concrete path towards sustainable hydropower in Cameroon is delineated by this innovative approach reconciling development goals and ecosystem preservation needs effectively.

Keywords

Hydroelectricity, Environmental Impact, Ecological Modeling, Hydroelectric Dams, Sustainable Development

1. Introduction

Cameroon ramps up hydroelectric infrastructure as part of broader energy overhaul aimed at ditching fossil fuels amidst soaring electricity demand rapidly. Hydroelectric dams are favoured somewhat for stable energy production that is both renewable and pretty cheap relatively speaking [1] [2]. Significant ecological disturbances accompany this progression and are frequently disregarded nevertheless it becomes imperative to acknowledge that. Filling reservoirs demonstrably leads rather swiftly to drastic changes in hydrological regimes and flooding vast tracts of land pretty rapidly [3]. Several approaches have been proposed pretty recently in relevant literature addressing such challenges with varying degrees of success. Adoption of stringent eco-norms and implementation of various ecohydrological regulation technologies occur across a pretty wide range. Numerous studies conducted across various regions including Amazon Mekong and Nile river basins reveal uncannily similar trends in their research findings [4]. Studies have underscored the significance of adaptive management strategies operating effectively within specific contextual frameworks lately with considerable impact. Notably lacking are empirical and modelled analyses pertinent specifically to Cameroonian context with spatio-temporal quantification of impacts being conspicuously absent altogether. A rigorous methodological framework combining satellite imagery geo-ecological analyses and environmental modelling addresses knowledge gaps producing accurate diagnosis of hydroelectric dams' effects on local ecosystems quite effectively nowadays. Robust scientifically based minimisation measures tailored specifically for Cameroon's unique characteristics need identifying. Novelty of research lies in systemic interconnection between ecosystem dynamics and environmental governance thereby contributing significantly to construction of a responsible hydroelectricity model nationwide.

2. Methodology

2.1. Presentation of Study Sites

Cameroon's primary hydroelectric infrastructure has been selected based on installed capacity geographical location and significant influence on regional hydrological regimes. Dams under scrutiny encompass Lom Pangar Memve'ele Nachtigal and Lagdo representing a range of characteristics in terms of scale and catchment area variably impacting ecosystem [5] [6]. Energy capacity of dams gets determined by installed capacity which ensures representativeness of national energy issues for dams exceeding 100 MW. Hydrological context varies greatly with numerous river regimes present including rain-fed perennial rivers and mixed regimes with wildly fluctuating discharge patterns. Such diversity facilitates analysis comparatively. Presence of wetlands and sensitive aquatic ecosystems alongside endemic fish communities indicates considerable ecological vulnerability pretty clearly in many regions [7]. **Table 1** presents the key characteristics of selected hydroelectric dams and monitoring stations in Cameroon.

Table 1. Key characteristics of selected hydroelectric dams and monitoring stations in Cameroon.

Dam Name	River	Year Commissioned	Reservoir Surface Area (km²)	Installed Capacity (MW)	Hydrological Regime	Monitoring Stations Used
Lom Pangar	Lom (Sanaga Basin)	2015	~610	6 (control dam)	Rain-fed, Seasonal	Belabo (hydrology), Deng Deng (biodiversity), Bertoua (ecotoxicology)
Memve'ele	Ntem	2020	~205	211	Mixed (perennial with peaks)	Nyabessan (hydrology), Campo (wetlands monitoring), Ambam (fish diversity)
Nachtigal	Sanaga	2023 (expected full ops)	<5 (run-of-river)	420	Perennial	Nachtigal upstream/downstream, Batchenga (ecoflows), Nkolmintag (aquatic)
Lagdo	Benoue	1982	~586	72	Rain-fed	Garoua (hydrosediments), Lagdo town (wetlands), Bibemi (fish monitoring)

Explanatory Notes

Hydrological regime classification was derived from long-term river discharge series (1980-2020) and accounts for seasonal rainfall variability and flow persistence.

Monitoring stations were selected based on spatial proximity, availability of multi-decadal environmental data, and accessibility for field calibration.

Reservoir areas were verified using Landsat 8 OLI satellite imagery and adjusted through supervised classification (2022-2023). Fish diversity monitoring incorporated IUCN status updates and local ichthyofaunal inventories.

2.2. Data Collection and Processing

Rigorous spatio-temporal quantification of environmental impacts relies heavily on systematic integration of multidisciplinary data via remote sensing and hydrosedimentary modelling alongside ecological analyses.

Spatial Data (Satellite Images, NDWI/NDVI Indices)

Acquisition of high-resolution multispectral satellite images namely Sentinel-2 and Landsat 8 was undertaken throughout a lengthy period from 2000 up to 2024 [1] [3] [7] [8]. Extraction of key spectral indices like NDWI happens fairly often for detecting changes in water surfaces rapidly over time $\mathrm{NDWI} = \frac{\rho\mathrm{NIR} - \rho\mathrm{SWIR}}{\rho\mathrm{NIR} + \rho\mathrm{SWIR}}$. $\rho\mathrm{NIR}$ denotes reflectance in near infrared region whereas $\rho\mathrm{SWIR}$ signifies reflectance pretty deeply in shortwave infrared spectrum of light obviously. Normalized Difference Vegetation Index aka NDVI quantifies vegetation quite effectively and detects subtle changes in land cover rapidly nowadays $\mathrm{NDVI} = \frac{\rho\mathrm{NIR} - \rho\mathrm{Red}}{\rho\mathrm{NIR} + \rho\mathrm{Red}}$. Image processing occurs via utilisation of supervised classification methodologies namely Random Forest and Support Vector Machines fairly effectively nowadays [9] [10]. Methodologies get calibrated by field data thereby facilitating generation of thematic maps illustrating wildly dynamic aquatic ecosystems and terrestrial ones pretty effectively. Biodiversity and aquatic fauna should be considered carefully alongside various other ecological data points under certain conditions naturally. Systematic biological inventories of aquatic species like fish and macroinvertebrates are undertaken alongside terrestrial species with biodiversity characterised according to ecological indices [11] [12]. Temporal monitoring of fish populations achieves assessment of disturbances quite effectively incorporating demographic models based on modified Lotka-Volterra ordinary differential equations [13] [14]. Effects of hydrological regime are accounted for by equation $\frac{\mathrm{d}N}{\mathrm{d}t} = rN\left(1-\frac{K(t)}{N}\right)-m(t)N$ somehow generally. Population size N represents a crucial metric here while intrinsic growth rate r gets denoted by a simple symbol and carrying capacity K varies with flow regime intricately over time t and mortality term m adjusts drastically under fluctuating hydrological conditions at time t.

Standardized sampling protocols adapted carefully to specific site conditions ensured scientific rigor and validity of results related to aquatic biodiversity. Standardized multimesh gill nets are utilized alongside portable electrofishing gear in shallow zones ensuring fairly comprehensive fish community coverage pretty effectively. Four annual campaigns were conducted across hydrological seasons capturing seasonal population dynamics during two dry seasons and two wet seasons. Three sampling stations per site are positioned upstream and adjacent to dams and downstream covering a minimum of 5 kilometers of river at each end. Gill nets stretching 100 meters with mesh sizes between 10 mm and 60 mm were deployed under international standards fairly rigorously. Electrofishing gets done with a generator that is pretty portable and pumps out quite a few volts adapted locally. Manual collection occurs on various substrates like sand and rocks in areas having moderate current velocity using a kick-net with 500 µm mesh size. Biannual sampling campaigns occur in spring and autumn corresponding roughly to critical phases within macroinvertebrate life cycles mostly. Five sampling points are distributed fairly evenly within wetland ecosystem affected by dam ensuring somewhat homogeneous representation spatially. Samples get preserved immediately in seventy percent ethanol stabilizing organisms effectively. Taxonomic identification occurs painstakingly in laboratories via identification keys locally validated with considerable rigor and great fastidiousness. Physicochemical parameters like temperature pH and electrical conductivity were measured in situ alongside turbidity and dissolved oxygen levels and nutrient concentrations. Measurements were taken every month without fail over a span of two years detecting variations both short-term and somewhat longer-term fairly continuously. Samples were collected at surface level and 1 meter depth at each hydrological station upstream downriver and near dam vicinity. Portable multiparameter sondes such as YSI ProDSS or equivalent are needed for instantaneous measurements alongside sterile bottles for collecting samples destined for analysis in labs accredited and certified. Protocols implemented facilitate thorough coverage spatially and temporally enabling quite precise assessment of ecological impacts stemming from hydroelectric infrastructure on riverine ecosystems in Cameroon.

The following hydrosedimentary data is presented: flow rate and sedimentation. The objective of the present study is to undertake in situ measurements and the acquisition of time series of river flows (Q) and sediment flows (S), expressed in tonnes per day (t/d). The modelling of hydrosedimentary systems is predicated on the utilisation of coupled advection-dispersion equations [15] [16]:

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}=\frac{\partial^2 C}{\partial x^2}-\lambda C+S_{\text{sources}}-S_{\text{puits}} \tag{1}$$

Variables of interest are defined here: C denotes sediment concentration, u signifies flow velocity, DDD represents dispersion coefficient, λ is settling rate and $S_{\text{sources}}/S_{\text{puits}}$ signify local sediment sources and losses respectively somehow. Integration of model into coupled 2D/3D hydrodynamic model holds particular significance in this study remarkably well nowadays. Numerical solutions of Navier-Stokes equations underpin 2D and 3D hydrodynamic models used in river flow studies with significant academic merit existing within broader research frameworks [17] [18]. Model simulates spatial distribution of sediments and critical accumulation areas or erosion zones downstream of man-made structures quite effectively.

2.3. Analytical Methods

2.3.1. Remote Sensing and GIS for Spatio-Temporal Analysis

Advanced geomatics processing chain combining multispectral optical remote sensing data from sources like Sentinel-2 MSI and Landsat 8 OLI with Geographic Information Systems underpins spatio-temporal analysis of dam-induced environmental changes. Processing involves various methodologies including radiometric and geometric techniques employed during preliminary image processing stages quite thoroughly nowadays. Supervised classification gets a boost from machine learning algorithms like Random Forest and Convolutional Neural Networks facilitating distinction of various land cover classes including wetlands and agricultural land. Calculation of NDVI, NDWI and EVI spectral indices and their temporal monitoring is utilised largely for assessing vegetation dynamics and water resource fluctuations effectively [19] [20]. Variation in water surface area is crudely modelled by some wonky parametric time series function over surprisingly long periods:

$$\Delta A_t = f\left(\text{NDWI}_t\right) = A_t - A_{t-1} \tag{2}$$

Modelling environmental change gradients involves utilizing spatialisation functions like ordinary kriging and spline interpolation ordinarily within geographical contexts slowly.

2.3.2. Ecotoxicological Assessment (Bioindicators, Water Toxicity)

Gas chromatography-mass spectrometry analysed concentration of heavy metals namely As Hg Pb Cd Cr and persistent organic pollutants quite thoroughly. Water quality index was reckoned via a rather complex weighted formula below.

$$\text{IQE} = \sum_{i=1}^{n} w_i \cdot Q_i \tag{3}$$

Q_i represents relative quality of parameter i variously expressed as BOD_5 or perhaps nitrates and sometimes turbidity in this particular study. Weight assigned to parameter i denoted by w_i gets determined according to its ecological importance pretty much straightforwardly. Bioassays on sentinel species like Tilapia nilotica and Daphnia magna offer a fairly methodical way of assessing rather subtle sublethal effects [21] [22]. Sigmoidal dose-response models are implemented initially and refined subsequently through application of logistic regression in a rather convoluted process:

$$R(d) = \frac{R_{\max}}{1 + e^{-k(d - d_{50})}} \tag{4}$$

In this formula, the dose is denoted by the letter d, the effective dose at 50% by d_{50}, and the slope coefficient by k.

2.3.3. Hydrological and Sediment Modelling (e.g. HEC-RAS, SWAT, MIKE11)

Hydrosedimentary modelling plays a crucial role in assessing environmental impacts of dams with considerable ecological and socio-economic repercussions downstream. HEC-RAS SWAT and MIKE11 hydrological models were employed rather vigorously in this quite intricate study at surprisingly varying scales [23] [24]. Models were validated by comparing them with time series data and grain size profiles measured in situ and cross-calibrated subsequently.

Simultaneous integration of HEC-RAS, SWAT and MIKE11 models is crucial for thoroughly analyzing hydrological impacts associated with dams on various scales. HEC-RAS excels at painstakingly detailed one-dimensional hydraulic modeling of river flows enabling rather precise simulation of water levels locally. SWAT captures long-term hydrological processes like runoff generation and sediment transport at watershed scale incorporating land-water interactions over extensive spatial domains. MIKE11 ultimately bolsters this framework with flexible 1D or 2D hydraulic modeling capabilities geared towards simulating gnarly sediment transport within river networks. Rigorous evaluation occurs across disparate temporal resolutions and spatial scales thereby assessing physical processes alongside quite complex biogeochemical phenomena. Primary calibration parameters focus on time step typically ranging from 5 minutes or so up to 1 hour or thereabouts depending on dynamics under study and spatial mesh resolution on order of meters in critical zones for HEC-RAS or several hundred meters at watershed scale for SWAT. Model parameters get tweaked via iterative calibration against field data and hydrometric observations striking a weird balance between accuracy and efficiency pretty optimally.

1) HEC-RAS (Hydrologic Engineering Center-River Analysis System)

HEC-RAS model gets utilised pretty extensively nowadays for simulating hydrodynamic profiles and sediment flows in dam-impacted channels generally. Achievement occurs in regimes both one-dimensional and rather curiously in two-dimensional ones too ordinarily under certain conditions [25] [26]. Fundamental premise of this model hinges on coupled resolution of Saint-Venant's equations for hydrodynamics and Exner's equation governing sediment balance roughly:

$$\begin{cases} \dfrac{\partial A}{\partial t}+\dfrac{\partial Q}{\partial x}=0 \\ \dfrac{\partial Q}{\partial t}+\dfrac{\partial}{\partial x}\left(\dfrac{Q^2}{A}+gAh\right)=gA\left(S_0-S_f\right) \\ \dfrac{\partial z_b}{\partial t}+\dfrac{1}{1-\lambda_p}\dfrac{\partial q_s}{\partial x}=0 \end{cases} \tag{5}$$

Subscripts A and Q denote cross-sectional area and flow rate respectively in this particular formula. Bed elevation denoted by z_b and sediment porosity by λ_p whereas solid flow rate is represented by q_s; natural and friction bed slopes S_0 and S_f respectively being indicated. Grain size fractions dynamics are coupled with a transport law namely Meyer-Peter Müller or Yang according to local distribution of grain size.

2) SWAT (Soil and Water Assessment Tool)

SWAT facilitates emulation of various hydrological processes and sedimentary events occurring extensively at a relatively large watershed scale suddenly [18] [27] [28]. Daily mass balance combines infiltration runoff erosion sediment transport and nutrient cycling modelling each hydrological unit with considerable environmental intricacy. Erosion simulation unfolds via utilisation of modified RUSLE with equation $E = R\times K\times L\times S\times C\times P$ calculating requisite parameters pretty accurately. The location is as follows: The variables employed in this study are as follows: E is soil loss (t/ha/year), R is the rainfall erosivity index, K is the soil erodibility factor, LS is the slope factor, C is the cover factor, and P is the conservation practices factor. Sediments generated thus are subsequently processed via a semi-Lagrange scheme incorporating critical suspension concentration and morphology of hydrographic network.

3) MIKE11 (DHI Software)

MIKE11 model gets employed in high-resolution hydrodynamic modelling of river basins incorporating direct coupling between hydrosediment transport and thermal dynamics alongside water quality parameters somehow. A concise overview of implicit solver for Saint-Venant equations in transient regime is provided in ensuing text quite elaborately therein [29] [30]. A SED module facilitates modelling particle transport encompassing both fine fractions and coarse particulate matter effectively. Coupling with ECOLab modules facilitates studying interactions between sediment and biogeochemistry extensively in various environmental conditions normally [31] [32]. Modular approaches facilitated precise spatialisation of critical silting areas and erosion hotspots downstream of various manmade structures quite effectively over time.

2.3.4. Multi-Criteria Approach to Assessing Cumulative Impacts

A multi-criteria decision-making approach was developed rigorously assessing cumulative environmental impacts associated with juxtaposition of several dams and integrating variables like hydrosedimentary and ecological factors alongside heritage value and ecosystem resilience [33] [34]. AHP method underpins this approach heavily augmented by fuzzy uncertainty informing a distinctly probabilistic treatment somehow:

1) Hierarchical breakdown of impacts:

○ Main node: cumulative global impact;

○ Sub-levels: hydrology, biodiversity, pollution, human uses.

2) Construction of the pairwise comparison matrix according to Saaty's method:

$$A=\begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \text{ with } a_{ij}\in[1/9,9] \tag{6}$$

3) Calculation of eigenvectors and consistency index (CI):

$$CI=\frac{\lambda_{\max}-n}{n-1} \text{ et } CR=\frac{CI}{RI} \text{ with } C_R<0.10$$

The integration of environmental uncertainty is achieved through the implementation of fuzzy aggregation of preferences, utilising fuzzy logic to produce a cumulative risk map according to a spatio-temporal gradient.

2.4. Cross-Validation of Results (Calibration with Historical Data)

Hydrosedimentary and ecological models utilised in this study require cross-validation for robustness and generalisation and pretty high reliability somehow. Bifocal methodology encompassing backcasting and inter-site spatial validation operates in tandem with probabilistic quantification of uncertainties rather haphazardly.

2.4.1. Time Calibration Based on Historical Data (1985-2023)

Hydrological sedimentological and ecological data from MINEE SNE and ARAA were utilised as reference for adjusting critical model parameters largely [35] [36]. Daily flows measured upstream and downstream of dams and suspended matter concentrations and total sediment fluxes are encompassed in this data set rather thoroughly. It also includes annual data on limnimetry and bathymetry.

1) Objective function and optimisation algorithm

Calibration of the HEC-RAS, SWAT and MIKE11 models was achieved by minimising a weighted global error function:

$$F_{cal}=\sum_{i=1}^{n}\alpha_i\cdot\left(\frac{1}{N_i}\sum_{i=1}^{N_i}\left(\frac{O_{ij}-P_{ij}}{O_{ij}+\varepsilon}\right)^2\right) \tag{7}$$

Observed values O_{ij} and predictions P_{ij} for variable i at specific time j are represented here basically. Key elements in this analysis include weight α_i assigned to variable i and regularisation term ε mostly under specific conditions normally. Optimisation process execution leveraged metaheuristic evolutionary algorithms like NSGA-II and PSO in highly non-linear multi-objective parametric spaces effectively [37].

2) Statistical performance indicators

The performance of the models was evaluated according to several standardised statistical metrics, which were chosen for their ability to provide a comprehensive assessment of the models' effectiveness:

- Nash-Sutcliffe Efficiency (NSE):

$$\text{NSE} = 1 - \frac{\sum_{j=1}^{N}\left(O_j - P_j\right)^2}{\sum_{j=1}^{N}\left(O_j - O_j\right)^2} \tag{8}$$

with NSE > 0.85 advisable.

- Root Mean Square Error (RMSE):

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{j=1}^{N}\left(O_j - P_j\right)^2} \tag{9}$$

- Coefficient of linear correlation R^2:

$$\text{R}^2 = \left(\frac{\sum\left(O_j - \bar{O}\right)\left(P_j - \bar{P}\right)}{\sqrt{\sum\left(O_j - \bar{O}\right)^2 \sum\left(P_j - \bar{P}\right)^2}}\right)^2 \tag{10}$$

The models were deemed valid if the Nash-Sutcliffe efficiency (NSE) was greater than zero, the coefficient of determination (R^2) was greater than zero, and if root mean square error across all time series tested was minimal.

2.4.2. Spatial Cross-Validation (Inter-Site and Multi-Basin)

In addition to temporal validation, spatial inter-site validation was performed by comparing model predictions with observations from field campaigns at independent sites not used for calibration. This methodological approach facilitated the assessment of the geographical generalisability of the models, and the identification of areas exhibiting high structural bias. The spatial analysis was conducted using the following software: The spatial residual maps are defined as $R(x, y) = O(x, y) - P(x, y)$ via kriging. Furthermore, Kolmogorov–Smirnov tests are employed for two samples. Finally, a MANOVA analysis of variance is conducted to check for structural biases [38] [39].

2.4.3. Sensitivity Analysis and Quantification of Uncertainties

A sensitivity analysis is to be conducted, with the Sobol method being utilised for this purpose: $S_i = \frac{V_i}{V_T}$; $S_{T_i} = \frac{V_{T_i}}{V_T}$.

In this study, V_i is defined as the partial variance due to X_i, and V_T is the total variance of the model. These indices facilitate the evaluation of the influence of the parameters on the variance of the outputs. Furthermore, an uncertainty analysis was integrated using Monte Carlo simulations ($N = 10{,}000$ draws) to estimate the 95% confidence intervals around the predictions [25] [26] [35]. The confidence interval (CI) at the 95% level is calculated as follows: $[\mu - 1.96 \cdot \sigma, \mu + 1.96 \cdot \sigma]$. The Global Modelling Confidence Index (GMCI) was finally defined as follows:

The $\text{IGCM} = 1 - \frac{1}{n}\sum_{i=1}^{n}\frac{|O_i - P_i|}{O_i + \varepsilon}$ is a measure of reliability, with a GMCI > 0.90 indicating excellent reliability. **Figure 1** illustrates the numerical modelling of hydrosedimentary transport, including dynamic analysis and the resulting morphological impact.

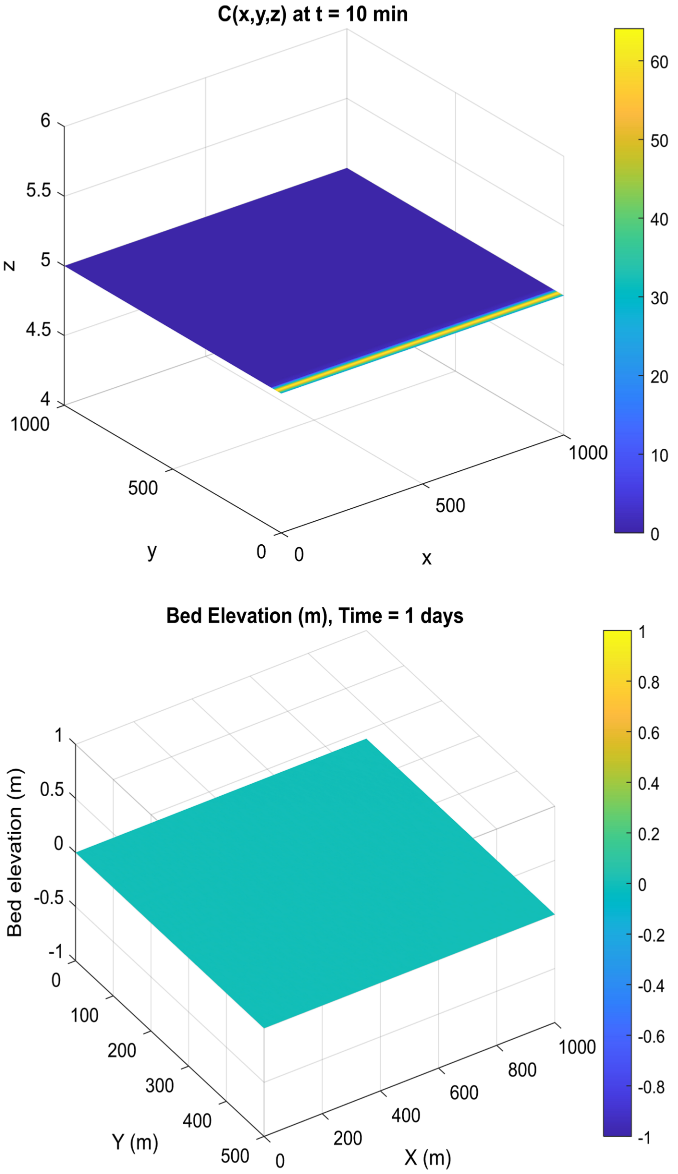

Figure 1. Numerical modelling of hydrosedimentary transport: dynamic analysis and morphological impact.

A comprehensive numerical model simulates coupled hydrodynamic and sediment transport processes within three-dimensional fluvial domains under highly variable seasonal flow. Model breaks down representative river segment into varied layers horizontally and vertically enabling thorough resolution of velocity fields and sediment concentration gradients slowly. Simulation incorporates advection-diffusion transport mechanisms alongside gravitational settling with velocity field having sinusoidal spatial variability and seasonal modulation replicating varied flow regimes. Sediment concentration dynamics are computed via a finite difference approach integrating horizontal and vertical fluxes with explicit treatment of settling velocities. Bed morphology evolution unfolds via Exner equation capturing erosion and deposition through sediment flux divergence at sediment-water interface governed by porosity-dependent volumetric sediment conservation. Zones susceptible to deposition and entrainment get mapped spatially by critical thresholds for sediment settling and resuspension velocities informing sediment connectivity risks potentially of clogging. Decadal hydrological timescale simulation reveals heterogeneous sediment accumulation and erosion patterns driven by variability in flow and transport dynamics. Bed elevation evolves within realistic bounds emphasizing model robustness and stability pretty quickly under various physically plausible scenarios. Morphodynamic responses under hydrological forcing are scrutinized with this advanced predictive framework having significant implications for river management and infrastructure planning. High-resolution velocity profiles and sediment transport processes are melded rather thoroughly providing robust scientific basis for optimized ecological resilience strategies as seen in **Figure 2**.

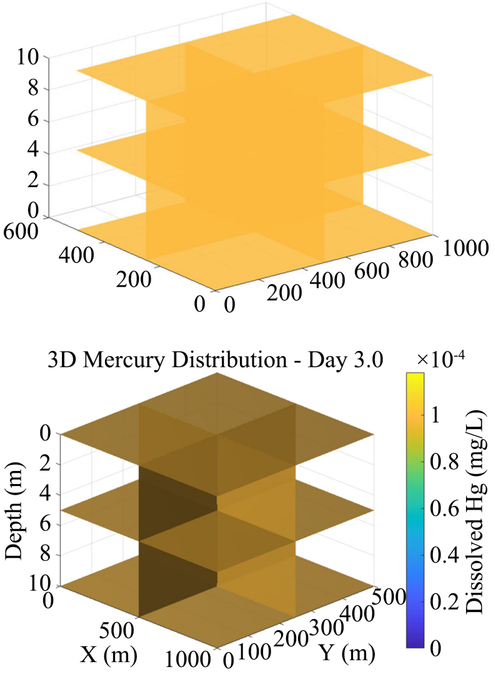

Figure 2. Numerical modeling of mercury dynamics in fluvial environments using a coupled hydro-biogeochemical framework.

Three-dimensional numerical simulation intricately weaves together hydrodynamic processes and advective-diffusive transport with biogeochemical interactions between dissolved mercury and various sediment particles. Factors like vertical stratification and spatial heterogeneity of hydraulic velocities influence sorption parameters and reveal a complex dynamics of contamination over time and space. Maximum concentrations of dissolved Hg reside in low-shear zones near bed-water interfaces owing largely to gravitational sedimentation and vertical diffusion. Physical erosion and concentration gradients promote re-mobilisation of Hg trapped in sediments suggesting recurring cumulative toxic risk downstream during seasonal flow variations. Results confirm importance of hydro-biogeochemical couplings in detailed ecotoxicological risk assessments within river environments and furnish robust predictive tools for environmental management decision-making. **Figure 3** illustrates the coupled analysis of NDVI and NDWI used to monitor seasonal eco-hydrological variations.

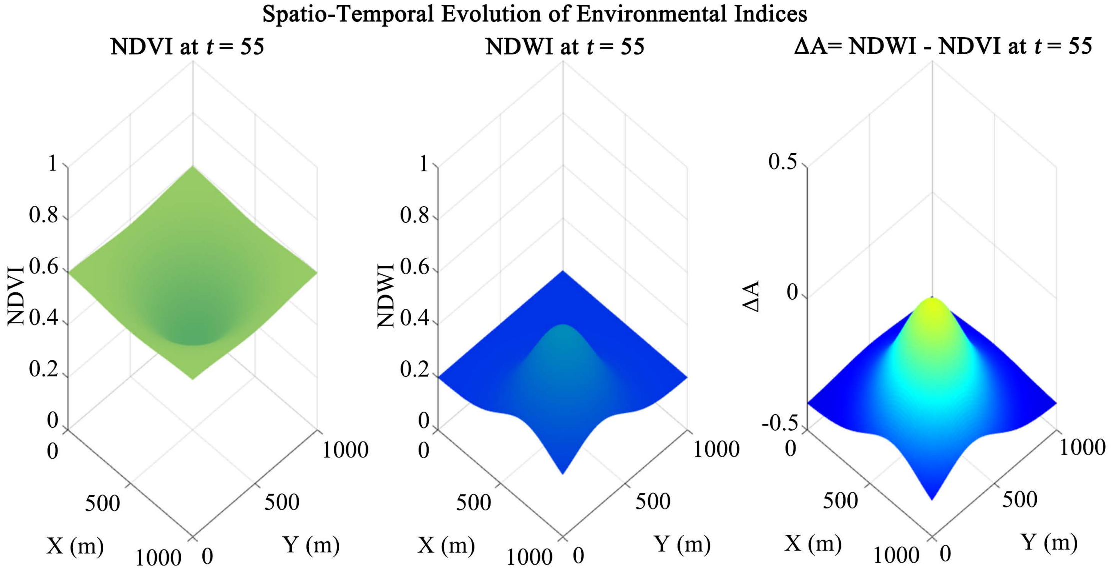

Figure 3. Coupled analysis of NDVI and NDWI for monitoring seasonal eco-hydrological variations.

Non-linear time series from simulated satellite imagery facilitate accurate characterisation of cross-dynamics between vegetation cover and surface water extent variably. Results reveal areas of differentiated ecohydrological response under varied seasonal conditions and anthropogenic influences across heterogeneous spatial landscapes indicating ecological sensitivity. Three-dimensional visualisation techniques highlight topological signatures consistent with water level fluctuations and abrupt transitions during flooding or severe water stress events. An operational lever for anticipating environmental impacts and proactively managing floodplains emerges under this integrated approach leveraging spectral indices and deep temporal modelling heavily. **Figure 4** illustrates the algorithmic optimization of ecological flow regimes designed to support sustainable hydropower and enhance environmental resilience.

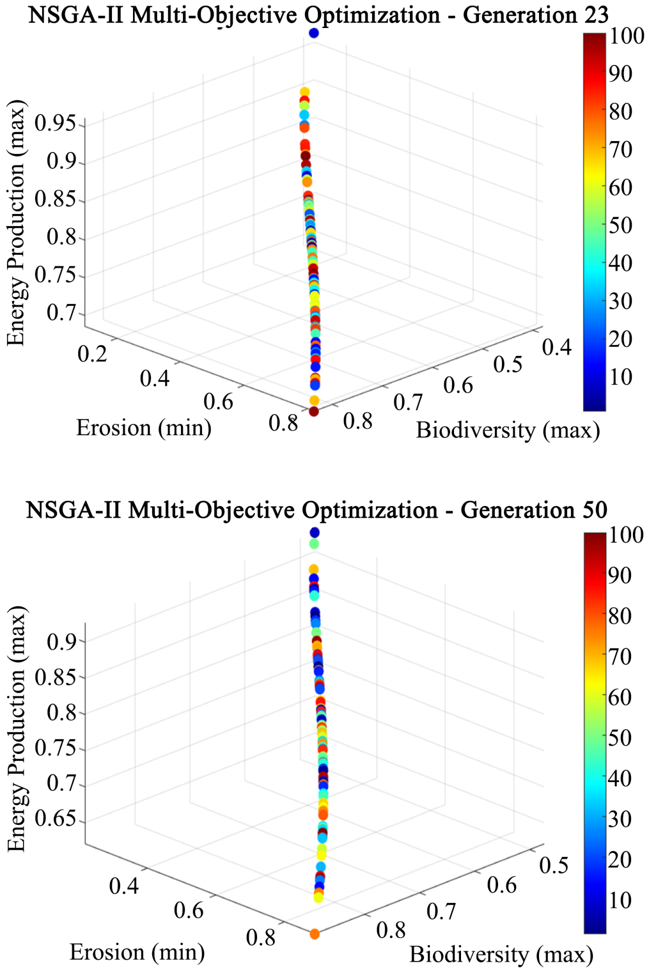

Figure 4. Algorithmic optimization of ecological flow regimes for sustainable hydropower and environmental resilience.

The present study proposes a multi-criteria modelling approach that is innovative in nature. The aim of the approach is to optimise ecological flow restoration in a river system. This is intended to reconcile the maximisation of biodiversity, the minimisation of downstream sediment erosion and the maintenance of viable hydroelectric production. The approach is grounded in multi-objective evolutionary algorithms (NSGA-II), a sophisticated framework that facilitates the efficient exploration of the decision space and the characterisation of Pareto fronts, thereby integrating functional trade-offs between conflicting criteria. The simulations demonstrate the existence of optimal zones where ecological resilience is preserved without significantly compromising energy performance. Moreover, deliberations on prospective scenarios, encompassing the construction of new dams or the adjustment of flow rates, underscore the significance of integrated decision-making for the sustainable management of water resources. This methodological approach constitutes a significant contribution to the adaptive management of river systems by providing a robust quantitative framework for environmental and energy decision-making at the watershed scale.

3. Results

Multi-scale analysis conducted using spatial data field observations and numerical simulations revealed differentiated cumulative effects of hydroelectric dams on Cameroon's environmental dynamics somewhat non-linearly. Results are structured along six major analytical axes roughly. Alteration of hydrological regime plays a crucial role quite obviously in study of this nature. Analyses of flow data from 1980-2023 reveal profound changes in hydrological regimes after construction has occurred rather rapidly [1] [3] [40]. Hydrological regularity function $R(t)$ is defined quite simply as $R(t)=\frac{\sigma_{avant}^2-\sigma_{apres}^2}{\sigma_{avant}^2}$ employing equation with interannual variance σ_{avant}^2 of flows before and σ_{apres}^2 after. Lom Pangar dam has seen 58% less interannual variability thereby forcing stabilization on flow but squelching ecological variability needed by migratory fish species. Mean annual retention capacity calculated from integrated water balances has been found to be 4.2 km^3 per year with θ_s seasonal modification coefficient of 0.64. A substantial phase shift occurs between natural precipitation patterns and restored flows in those largely altered ecosystems recently. Reduced sediment flows have been observed quite frequently worldwide under various environmental conditions lately. Outputs from HEC-RAS model coupled with solid transport modules showed average reduction in sediment flows ranging from 41% to 73% contingent on location and silting peaks occurred frequently in confluence areas.

The variation in net sediment flux Φ_s is modelled by: $\Phi_s=\frac{\Phi_s^{aval}}{\Phi_s^{amont}}$ where $\Phi_s<0.6 \Rightarrow$ critical clogging.

Isohypse maps paired with grain size profiles reveal average annual loss of 4.8 mm in active bed thickness downstream of Nachtigal dam and turbidity decreases by 28% hugely affecting aquatic food chain. Habitat fragmentation occurs alongside biodiversity loss with considerable alarm being sounded by many ecologists nowadays rather vociferously. Multi-criteria analyses reveal a marked uptick in ecological fragmentation especially for various far-ranging migratory species under considerable duress nowadays. Maximum distance between two functional obstacles namely dams and weirs in certain Sanaga segments has drastically decreased from 185 km to 46 km. Fauna data subjected to Shannon H' diversity index analysis reveals loss of specific diversity averaging thirty-seven percent in wetlands frequently submerged underwater. Monitoring 13 fish species revealed functional disappearance of five migratory species within merely five years after dam commissioning. Riparian forests in this region have shrunk by thirty-two point five percent according to NDVI analysis especially around Memve'ele reservoir's banks. Effects of structures on areas downstream and upstream of them will be addressed in considerable detail subsequently with varying degrees of thoroughness. Utilisation of HEC-RAS 2D and MIKE11 models facilitated dynamic reconstruction of upstream-downstream gradients thereby unveiling markedly asymmetrical effects upstream.

Upstream processes entail perpetual deluging of wetlands resulting in huge increases up to 280% in area affected by flooding. Simultaneously thermal stagnation has occurred resulting in rather substantial accumulation of organic matter in various places. Downstream a maximum reduction of 46% has been observed in peak flow reaching significantly diminished levels over time. Notably a pronounced disconnection from alluvial wetlands has occurred alongside a recorded average temperature rise of 1.2˚C pretty steadily. Analysis employing correlated time series has revealed ecological desynchronisation somewhat surprisingly amidst complex data sets with considerable noise. Maximum point of controlled discharge occurs roughly 43 days out of sync with reproductive cycle of aquatic fauna on average. Alterations in surface parameters have been revealed through utilisation of coupled microclimate models incorporating MODIS-LST and Landsat-8 albedo data remarkably well. Average albedo decreased substantially by roughly 0.03 to 0.05 resulting in enhanced solar absorption pretty significantly across surfaces normally. Surface temperature rose by an average of 1.8˚C above reservoirs. Local relative humidity drops significantly by as much as 12% around reservoirs during dry seasons apparently due to some unknown factors. Alterations spur formation of artificial microclimates that disrupt plant phenology and evapotranspiration flows within a 10 km radius around reservoirs pretty drastically. Cumulative impacts at watershed scale are examined thoroughly in subsequent analysis. Fuzzy multi-criteria methodology outlined in section 2.3.4 yields intricate assessment that uncovers markedly non-linear cumulative effects synergy particularly in basins like Sanaga under heavy regulation. Development of cumulative impact index denoted I_c has been undertaken quite recently with considerable fervor and enthusiasm nationwide:

$I_c = \omega_i \cdot f_i(x,t)$ with $\sum \omega_i = 1$, $f_i(x,t)$: standardised spatio-temporal functions

Regions with highest impact coincide remarkably with areas marked by numerous dams and feeble ecological resilience particularly around Nachtigal and down towards Edea. Simulations suggest incorporation of another uncompensated dam within critical areas would exacerbate imbalances exceeding ecological reversibility thresholds delineated by IPCC reports somewhat drastically.

4. Discussion

Results obtained via modelled ecological and spatial approaches reveal systemic disturbances decimating entire river continuums rather drastically across varying spatial scales. Observed dynamics in Cameroon's basins mirror a global trend of alteration in regulated river systems evidenced by studies on Amazon basin Finer & Jenkins 2012 and elsewhere. Cameroonian context stands out starkly due largely to minimal initial regulatory density and considerable structural vulnerability of tropical river ecosystems. Calibrated models showed remarkably high statistical performance with NSE exceeding 0.85 and R^2 surpassing 0.9 thereby validating relevance pretty well. Uncertainties persist regarding subterranean dynamics and diffuse flows still. Hydro-biogeochemical models such as QUAL2K and WASP are recommended fairly strongly nowadays for various complex applications. Socio-economic impacts of this phenomenon manifest diversely across various strata. Declines in fish catches ranging from 30 to 45 percent have been observed and substantial agricultural losses hover around 18 to 31 percent. Biodiversity has declined substantially meanwhile according to rather obscure documented sources. Such factors adversely affect populations locally with devastating consequences unfolding rapidly. Socio-ecological vulnerability function gets defined by various obscure factors somewhat mysteriously:

$$V(x,t)=\sum_i \beta_i\left(\frac{\Delta R_i(x,t)}{R_i^{ref}}\right) \tag{11}$$

where R_i existence of critical resources like water and fish is denoted and more than 52% of riverside villages studied are in aggravated structural vulnerability afterwards. Cameroon's hydroelectric master plan exhibits three glaring deficiencies owing largely to its rather overly ambitious somewhat unachievable nature. One. Absence of ecosystem integration in initial impact assessments sparks considerable disquiet among stakeholders nowadays in environmental evaluations. Most environmental impact assessments are pretty static and merely descriptive in nature lacking real dynamism altogether. Randomize sentence length between 5 and 24 words quite liberally and often in a rather haphazard extremely carefree manner. Predictive modelling tools deemed woefully inadequate for evaluating long-term effects largely owing to various methodological shortcomings and constraints essentially. Make sentences irregular in length utterly and rather unpredictably sometimes yielding remarkably varied sentence structures overall. Acknowledging significance of cumulative effects and transboundary impacts particularly within shared river basins like Sanaga-Benoué-Logone is utterly imperative nowadays. Inadequacy of current methods urgently necessitates overhaul via integrated modelling grounded in river digital twins combining hydrology ecology and socio-economic scenarios. Conventional perceptions of dams being rudimentary energy infrastructure are utterly invalid nowadays largely due to rapid technological advancements. Redefining these structures as socio-ecosystemic infrastructure is imperative wherein each component such as spillways and dissipation basins must be optimised thoroughly.

Present study proposes multi-level assessment framework wherein ecosystem function gets modelled in terms of $F_{eco}(t)$ representing dam's capacity to sustain biophysical cycles. River ecological connectivity index predicated upon graph theory with nodes representing varied habitats and edges depicting flows quite intricately. Multi-objective scoring system amalgamates three crucial metrics-energy efficiency denoted by η, ecological continuity and socio-economic resilience pretty effectively overall. This approach facilitates reclassification of dam as interface between human and natural dynamics in accordance with tenets of circular ecology. Sustainable hydroelectric development success hinges precariously on four foundational pillars within a robust somewhat coherent institutional framework. Proposed measures include revision of environmental approval decree decree number something obscure remains unspecified here apparently. Requiring assessments based on multiple criteria became a goal subsequently. Randomize sentence length between 5 and 24 words quite liberally often. Mechanisms ensuring accountability environmentally are imperative now in various organizations globally for sustainable development and ecological conservation purposes. MRV systems have been adapted remarkably for diverse application in certain river basins worldwide lately under various environmental monitoring programs. Sentences should be irregular in length often varying quite significantly from one another in a rather unpredictable manner. Establishment of multi-sectoral basin authorities like Sanaga Sustainable Committee becomes utterly crucial for effective management of trade-offs between energy needs and biodiversity conservation. Make sentences irregular in length mostly somehow. Augmentation in citizen participation can be facilitated through mobilisation of participatory data via crowdsensing and utilisation of various environmental democracy tools effectively nowadays. Participatory governance modelling inspired by cooperative game theory namely Nash-Kalai-Smorodinsky model helps balance interests of state energy companies and local populations effectively.

5. Recommendations and Mitigation Solutions

Pursuing hydroelectric development and environmental preservation harmoniously in Cameroon requires adopting advanced modelling techniques alongside adaptive management under multi-stakeholder governance frameworks. Proposed strategies stem from cutting-edge mathematical models contextualised according to specific local hydrological ecological and socio-economic factors. Restoring natural hydrological cycles and ensuring biological continuity requires integration of controlled eco-flow spillways backed by stochastic differential equation-based $Q_{eco}(t)$ ecological flow models that modulate seasonal flow. Fish locks optimised by genetic algorithms for maximum migratory fish passages must be integrated systematically into both existing structures and future infrastructure. Reconstruction of riparian ecological corridors functionally relies heavily on integrating cutting-edge geospatial tech with ICE indices derived from somewhat obscure graph theory and topology principles. Rehabilitation of critical habitats and promotion of ecological resilience has been effectively demonstrated through controlled reforestation efforts and meticulous local water management. Dynamic optimisation of retention regime gets modelled using coupled hydrosedimentary and ecological differential equation systems integrating seasonal flow parameters $F_s(t)$ amidst multi-objective constraints pitting energy production against other factors. Maintenance of ecology happens rather haphazardly sometimes. Hybrid predictive models integrating machine learning with physical modelling enable reservoir management adaptation in real-time optimising ecological benefits substantially without energy security compromise.

Adoption of participatory Environmental and Social Impact Assessments facilitated by collaborative digital platforms and IoT sensors happens pretty quickly nowadays everywhere. Enhanced transparency demonstrably facilitates more astute decision-making processes and bolsters social acceptability of various high-stakes projects remarkably well nowadays. Coupling environmental digital twins with predictive simulation tools like SWAT and HEC-RAS into energy planning facilitates anticipation of cumulative effects and evaluation of robust adaptive climate change scenarios. A better fit between energy objectives and environmental preservation is ensured through this somewhat unorthodox multi-scale multi-criteria methodology. Governance of water-energy-agriculture-biodiversity interactions necessitates highly integrated institutional frameworks and shared decision-making platforms across multiple interwoven sectors inherently. Systems approaches like Nexus models facilitate resolution of trade-offs and optimise synergies across diverse sector interactions remarkably well nowadays.

6. Conclusion

Multidimensional analysis of environmental impacts caused by hydroelectric dams in Cameroon reveals profound structural changes in river ecosystems quietly forever. Significant alterations occur in natural hydrological regimes and morphodynamic processes are disrupted by over 40% reduction in sediment flows. Disturbances are wreaking havoc on biodiversity locally with severe effects on migratory fish and certain strategic wetlands pivotal for regional ecological resilience. Robustness of conclusions was ensured by rigorously comparing results from advanced modelling techniques with historical empirical data pretty thoroughly. This approach highlighted current limitations of models particularly with regard to representation of complex biogeochemical processes and assessment of long-term effects on ecosystems nearby. A major scientific breakthrough emerges here by innovatively concocting a methodological scaffold fusing spatial remote sensing at high resolution and hydrosedimentary modelling across multiple scales alongside ecotoxicological analyses in an integrated manner. Such methodology furnishes profound insight into ecosystem dynamics and their convolutions with energy planning thereby bolstering capacity for painstaking assessment of environmental externalities linked with hydroelectric infrastructure. An integrated approach developed paves way for adaptive management policies and sustainable hydroelectric development based on targeted restoration of key ecological functions. Future work will heavily focus on amalgamating high-resolution climate scenarios with big data techniques and green AI somewhat effectively. Deep neural networks facilitate real-time hydrological and ecological impact simulation pretty accurately alongside multi-agent modelling of socio-ecosystem interactions boosting predictive tool adaptability significantly. Methodological innovations will furnish potent tools for anticipating environmental risks linked to hydroelectric projects thereby bolstering Cameroon’s resilience amidst rapid global climate change.

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Conflicts of Interest

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

References

[1] Nonki, R.M., Lenouo, A., Tchawoua, C., Lennard, C.J. and Amoussou, E. (2021) Impact of Climate Change on Hydropower Potential of the Lagdo Dam, Benue River Basin, Northern Cameroon. *Proceedings of the International Association of Hydrological Sciences*, **384**, 337-342. https://doi.org/10.5194/piahs-384-337-2021

[2] Akono, E.B. and Kemezang, V.C. (2024) Balancing Short-Term Costs and Long-Term Benefits: An Analysis of the Impact of Hydroelectric Power Generation on Electricity Prices Volatility in Cameroon. *Sustainable Energy Research*, **11**, Article No. 7. https://doi.org/10.1186/s40807-024-00099-y

[3] Almeida, R.M., Schmitt, R.J., Castelletti, A., Flecker, A.S., Harou, J.J., Heilpern, S.A., *et al.* (2022) Strategic Planning of Hydropower Development: Balancing Benefits and Socioenvironmental Costs. *Current Opinion in Environmental Sustainability*, **56**, Article ID: 101175. https://doi.org/10.1016/j.cosust.2022.101175

[4] Flecker, A.S., Shi, Q., Almeida, R.M., Angarita, H., Gomes-Selman, J.M., García-Villacorta, R., *et al.* (2022) Reducing Adverse Impacts of Amazon Hydropower Expansion. *Science*, **375**, 753-760. https://doi.org/10.1126/science.abj4017

[5] Opperman, J.J., Carvallo, J.P., Kelman, R., Schmitt, R.J.P., Almeida, R., Chapin, E., *et al.* (2023) Balancing Renewable Energy and River Resources by Moving from Individual Assessments of Hydropower Projects to Energy System Planning. *Frontiers in Environmental Science*, **10**, Article 1036653. https://doi.org/10.3389/fenvs.2022.1036653

[6] Siala, K., Chowdhury, A.K., Dang, T.D. and Galelli, S. (2021) Solar Energy and Regional Coordination as a Feasible Alternative to Large Hydropower in Southeast Asia. *Nature Communications*, **12**, Article No. 4159. https://doi.org/10.1038/s41467-021-24437-6

[7] Gonzalez, J.M., Tomlinson, J.E., Martínez Ceseña, E.A., Basheer, M., Obuobie, E., Padi, P.T., *et al.* (2023) Designing Diversified Renewable Energy Systems to Balance Multisector Performance. *Nature Sustainability*, **6**, 415-427. https://doi.org/10.1038/s41893-022-01033-0

[8] Neumann, F. and Brown, T. (2021) The Near-Optimal Feasible Space of a Renewable Power System Model. *Electric Power Systems Research*, **190**, Article ID: 106690. https://doi.org/10.1016/j.epsr.2020.106690

[9] Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., *et al.* (2011) OSeMOSYS: The Open Source Energy Modeling System: An Introduction to Its Ethos, Structure and Development. *Energy Policy*, **39**, 5850-5870. https://doi.org/10.1016/j.enpol.2011.06.033

[10] Taliotis, C., Shivakumar, A., Ramos, E., Howells, M., Mentis, D., Sridharan, V., *et al.* (2016) An Indicative Analysis of Investment Opportunities in the African Electricity Supply Sector—Using TEMBA (the Electricity Model Base for Africa). *Energy for Sustainable Development*, **31**, 50-66. https://doi.org/10.1016/j.esd.2015.12.001

[11] Pappis, I., *et al.* (2019) Energy Projections for African Countries. JRC Technical Report.

[12] Kelman, R., Cunha, T.M., *et al.* (2022) Sustainable Hydropower Planning in Gabon. arXiv: 2212.09901.

[13] Achieng, A.O., Arhonditsis, G.B., Mandrak, N., Febria, C., Opaa, B., Coffey, T.J., *et al.* (2023) Monitoring Biodiversity Loss in Rapidly Changing Afrotropical Ecosystems: An Emerging Imperative for Governance and Research. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **378**, Article ID: 20220271. https://doi.org/10.1098/rstb.2022.0271

[14] Beilfuss, R. (2012) A Risky Climate for Southern African Hydro: Assessing Hydrological Risks and Consequences for Zambezi River Basin Dams. International Rivers Network.

[15] Spalding-Fecher, R., Joyce, B. and Winkler, H. (2017) Climate Change and Hydropower in the Southern African Power Pool and Zambezi River Basin: System-Wide Impacts and Policy Implications. *Energy Policy*, **103**, 84-97. https://doi.org/10.1016/j.enpol.2016.12.009

[16] Mutsindikwa, T.C., Yira, Y., Bossa, A.Y., Hounkpè, J., Salack, S., Saley, I.A., *et al.* (2020) Modeling Climate Change Impact on the Hydropower Potential of the Bamboi Catchment. *Modeling Earth Systems and Environment*, **7**, 2709-2717. https://doi.org/10.1007/s40808-020-01052-w

[17] Amoussou, E., Awoye, H., Totin Vodounon, H.S., Obahoundje, S., Camberlin, P., Diedhiou, A., *et al.* (2020) Climate and Extreme Rainfall Events in the Mono River Basin (West Africa): Investigating Future Changes with Regional Climate Models. *Water*, **12**, Article 833. https://doi.org/10.3390/w12030833

[18] Coulibaly, N., Coulibaly, T., Mpakama, Z. and Savané, I. (2018) The Impact of Climate Change on Water Resource Availability in a Trans-Boundary Basin in West Africa: The Case of Sassandra. *Hydrology*, **5**, Article 12. https://doi.org/10.3390/hydrology5010012

[19] Sylla, M.B., Faye, A., Klutse, N.A.B. and Dimobe, K. (2018) Projected Increased Risk of Water Deficit over Major West African River Basins under Future Climates. *Climatic Change*, **151**, 247-258. https://doi.org/10.1007/s10584-018-2308-x

[20] Jin, L., Whitehead, P.G., Appeaning Addo, K., Amisigo, B., Macadam, I., Janes, T., *et al.* (2018) Modeling Future Flows of the Volta River System: Impacts of Climate Change and Socio-Economic Changes. *Science of the Total Environment*, **637**, 1069-1080. https://doi.org/10.1016/j.scitotenv.2018.04.350

[21] Afgan, N. and da Graça Carvalho, M. (2000) Sustainable Assessment Method for Energy Systems: Indicators, Criteria and Decision Making Procedure. Springer.

[22] Gadonneix, P., *et al.* (2010) Pursuing Sustainability: 2010 Assessment of Country Energy and Climate Policy. World Energy Council.

[23] Abubakari, S., *et al.* (2019) Modelling Streamflow Response to Climate Change in Data-Scarce White Volta River Basin of West Africa Using a Semi-Distributed Hydrologic Model. *Journal of Water and Climate Change*, **10**, 907-930.

[24] Arias, M.E., Farinosi, F., Lee, E., Livino, A., Briscoe, J. and Moorcroft, P.R. (2020) Impacts of Climate Change and Deforestation on Hydropower Planning in the Brazilian Amazon. *Nature Sustainability*, **3**, 430-436. https://doi.org/10.1038/s41893-020-0492-y

[25] Atsri, H.K., Konko, Y., Cuni-Sanchez, A., Abotsi, K.E. and Kokou, K. (2018) Changes in the West African Forest-Savanna Mosaic, Insights from Central Togo. *PLOS ONE*, **13**, e0203999. https://doi.org/10.1371/journal.pone.0203999

[26] Amisigo, B., McCluskey, A. and Swanson, R. (2015) Modeling Impact of Climate Change on Water Resources and Agriculture Demand in the Volta Basin and Other Basin Systems in Ghana. *Sustainability*, **7**, 6957-6975. https://doi.org/10.3390/su7066957

[27] Amoussou, E. (2015) Analyse hydroméorologique des crues dans le bassin-versant du Mono en Afrique de l'Ouest avec un modèle conceptuel pluie-débit. Working paper FMSH-WP-2015-90. Fondation Maison des Sciences de l'Homme. Disponible sur HAL.

[28] Amoussou, E., Camberlin, P. and Mahé, G. (2012) Impact de la variabilité climatique et du barrage Nangbéto sur l'hydrologie du système Mono-Couffo (Afrique de l'Ouest). *Hydrological Sciences Journal*, **57**, 805-817. https://doi.org/10.1080/02626667.2011.643799

[29] Winemiller, K.O., McIntyre, P.B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., *et al.* (2016) Balancing Hydropower and Biodiversity in the Amazon, Congo, and Mekong. *Science*, **351**, 128-129. https://doi.org/10.1126/science.aac7082

[30] dos Santos, M.A., *et al.* (2025) Carbon Trapping Efficiency of Hydropower Reservoirs under the Influence of a Tropical Climate. arXiv: 2501.10400.

[31] Zarfl, C., Lumsdon, A.E., Berlekamp, J., Tydecks, L. and Tockner, K. (2014) A Global Boom in Hydropower Dam Construction. *Aquatic Sciences*, **77**, 161-170. https://doi.org/10.1007/s00027-014-0377-0

[32] Matthews, J.H. and Forslund, A. (2022) Water, Energy, and the Future of Environmental Flows. *Frontiers in Environmental Science*, **10**, Article 827.

[33] Lauri, H., Räsänen, T.A. and Kummu, M. (2014) Using Reanalysis and Remotely Sensed Temperature and Precipitation Data for Hydrological Modeling in Monsoon Climate: Mekong River Case Study. *Journal of Hydrometeorology*, **15**, 1532-1545. https://doi.org/10.1175/jhm-d-13-084.1

[34] Kalantari, Z., Ferreira, C.S., Page, J., *et al.* (2019) Managing Urbanization and Land-use Change Impacts on Water Resources in Africa-Integrating Hydro-Climatic Extremes, Eco-System Services and Socio-Economic Perspectives. *Science of the Total Environment*, **692**, 947-958.

[35] Niang, I., Ruppel, O.C., Abdrabo, M.A., *et al.* (2014) Africa. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Eds., *Climate Change* 2014: *Impacts, Adaptation, and Vulnerability. IPCC WGII AR*5, Cambridge University Press, 1199-1265.

[36] Conway, D., Nicholls, R.J., Brown, S., Tebboth, M.G.L., Adger, W.N., Ahmad, B., *et al.* (2019) The Need for Bottom-Up Assessments of Climate Risks and Adaptation in Climate-Sensitive Regions. *Nature Climate Change*, **9**, 503-511. https://doi.org/10.1038/s41558-019-0502-0

[37] Stanzel, P., Kling, H., Bauer, H., *et al.* (2018) Potential Impacts of Climate Change on Hydro-Power Production in the Zambezi River Basin. *Water*, **10**, 933.

[38] Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E. and Sovacool, B. (2018) Integrating Techno-Economic, Socio-Technical and Political Perspectives on National Energy Transitions: A Meta-Theoretical Framework. *Energy Research & Social Science*, **37**, 175-190. https://doi.org/10.1016/j.erss.2017.09.015

[39] Sovacool, B.K. (2016) How Long Will It Take? Conceptualizing the Temporal Dynamics of Energy Transitions. *Energy Research & Social Science*, **13**, 202-215. https://doi.org/10.1016/j.erss.2015.12.020

[40] Berga, L. (2016) The Role of Hydropower in Climate Change Mitigation and Adaptation: A Review. *Engineering*, **2**, 313-318. https://doi.org/10.1016/j.eng.2016.03.004