A pragmatic approach to assess the climate resilience of hydro projects

Une approche pragmatique pour l'évaluation de la résilience climatique des projets hydrauliques

Pierre-Yves Bourgin[1*], et *Sandrine* Le-Clerc[1]

[1]ARTELIA, 6 Avenue de Lorraine, 98130 Echirolles, France

Abstract. There is no doubt that the planet is warming quickly. What is uncertain, and hugely so, is the impact the warming will have on the climatologic and hydrologic processes that directly influence performance of existing and planned water-resources related projects, for example hydropower. Therefore, the prospect of climate change has become a key issue for the large dams/reservoirs community. This paper provides first an overview of the increasing awareness of climate change impacts on the performance and reliability of hydro projects within this community. Then, it presents a pragmatic approach to assess the climate resilience of hydro projects. This approach fully complies with the Hydropower Sector Climate Resilience Guide released by International Hydropower Association in 2019 [1]. The case study is a hydropower project on St Paul River in Liberia. The paper focuses on the methods and results of the Phase 3 climate stress test, namely the power generation performance under a wide range of different possible future climate scenarios. The modelling cascade is formed by the hydrological model GR4J and a hydropower model supported by Mike Hydro Basin software. It is used to simulate 35+ years of daily hydropower operation.

Résumé. Il ne fait aucun doute que la planète se réchauffe rapidement. En revanche, il existe de fortes incertitudes sur les impacts que ce réchauffement aura sur les processus climatiques et hydrologiques qui influencent directement les performances des projets existants et futurs relatifs aux ressources en eau, comme les infrastructures hydroélectriques. C'est pourquoi la question du changement climatique est devenu un enjeu majeur au sein de la communauté des barrages-réservoirs. Cet article donne d'abord un aperçu de la prise de conscience croissante des impacts du changement climatique sur les performances des projets hydroélectriques au sein de cette communauté. Puis, l'article présente une approche pragmatique pour l'évaluation de la résilience climatique des projets hydroélectriques.

* Corresponding author: pierre-yves.bourgin@arteliagroup.com

Cette approche s'inscrit pleinement dans le cadre du Guide pour la résilience climatique édité par l'Association Internationale de l'Hydroélectricité en 2019 [1]. Le cas d'étude présenté dans cet article est un projet d'aménagement hydroélectrique sur le fleuve Saint Paul au Libéria. L'article se concentre sur les méthodes et les résultats du test de stress climatique (phase 3 du Guide), à savoir l'évaluation des performances du projet pour un vaste échantillon de scénarios climatiques futurs possibles. La chaine de modélisation est constituée du modèle hydrologique GR4J et d'un modèle de production supporté par le logiciel Mike Hydro Basin. Elle permet de simuler plus de 30 ans d'opérations journalières de l'aménagement hydroélectrique.

1 Introduction

The work of the Intergovernmental Panel on Climate Change (IPCC) demonstrates that global warming is unequivocal [2]. The climate projections indicate an increase in the global surface temperature of 2 ° C to 4.8 ° C at the end of the 21st century according to the emission scenarios considered and in relation to the average temperature over the period 1986-2005. Neither warming nor changes in precipitation will be uniform. In many mid-latitude regions and in arid or semi-arid subtropical regions, average rainfall is likely to decrease. Precipitation contrast between wet and dry regions and between wet and dry seasons will increase, although regional exceptions may exist.

Climate change will have a profound impact on the distribution and availability of water resources concerning both average and extreme events. While both developed and developing countries already face serious challenges in the water sector due to overexploitation of limited and unevenly distributed water resources, these challenges will be exacerbated in the future. The percentage change of water resources in a +2°C global warming future is given in Figure 1.

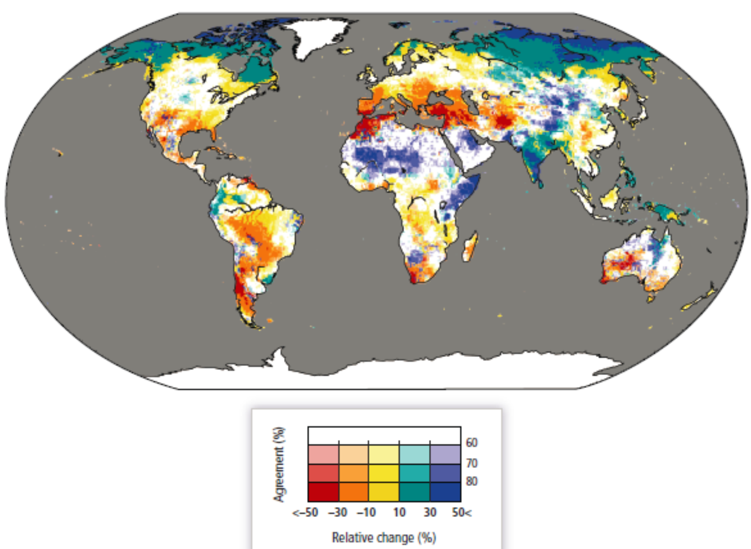

Fig. 1. Percentage change of mean annual streamflow for a global mean temperature rise of 2°C above 1980-2010. Color hues show the multi-model mean change while saturation shows the agreement on the sign of change across General Circulation Model (GCM) – Global Hydrological Models (GHM) combinations (source: [2]).

As a renewable energy fueled by river inflows, hydropower, like any water management system, strongly depends on hydrology:

- Changes in river flow (runoff volume, variability and seasonality of river flow) may affect directly the services.
- Changes in extreme events (floods and droughts) may increase the cost and risk.
- Changes in sediment loads due to changing hydrology could increase turbine abrasions, affect efficiency, and decrease reservoir regulation and storage services.

In many parts of the world, climate change is likely to exacerbate a reality already well known to designers and operators of major water management systems, that of hydrological risk linked to climate variability [3]. For example, the long drought that hit West Africa between the 1970s and the 1990s has had a lasting impact on the energy production of some large hydroelectric plants in the Ivory Coast (Buyo, Kossou) and Ghana (Akosombo). The same drought has caused significant changes in land use and vegetation cover in the Sahel region, permanently modifying the physical processes of infiltration and runoff. The scientific community has named this phenomenon the Sahelian paradox [4]. Associated with the established increase in the frequency of extreme rainfall in the region [5], this phenomenon may explain an increase in the hydrological risk of extreme flooding, like the August 1994 flood event at the Bagré Dam on the Nakambé River in Burkina Faso [6], which seriously tested the resistance of the structure and triggered safety works.

Also, one can think of the considerable damage, going as far as total destruction, caused in the mountain regions by torrential floods carrying very large quantities of materials. Glacier retreat in the Himalayan region caused by global warming [7] has been shown to be an aggravating factor for the risk of flash floods caused by the spontaneous rupture of a glacial lake.

The IPCC report on climate change impacts, adaptation strategies and vulnerability [8] shows that the global scale is poorly suited to analyzing the impacts of climate change on hydropower. Significant differences can appear within the same country, sometimes from the same watershed.

For a specific site, the impacts of climate change depend on the changes induced on the hydrological characteristics on the one hand, but also on the type of scheme (reservoir or run-of river) and the energy demand on the other hand, which is in turn affected by the impacts of climate change. The results of some emblematic studies are noted. For example, in the Zambezi River watershed, hydropower production could fall by 10% by 2030 and by 35% by 2050. Recent studies have sought to quantify the future evolution of hydropower generation on a global scale [9, 10] or regional [11, 12]. Some authors suggest a reduction of energy generation for 61-74% of hydropower plants around the world between 2040 and 2069 mainly due to a decrease in the river inflows.

2 Increasing awareness inside Dams/Reservoirs community

Practitioners of the dams and reservoirs sector are becoming increasingly aware of the issues related to climate change. Specifically, this trend is outlined by:

- The initiatives of the World Bank Group (WBG);
- The actions of the major professional associations: International Commission on Large Dams (ICOLD) and IHA;
- The increasing number of papers dealing with the subject in professional journals.

2.1 World Bank Group

Because it represents an unprecedented obstacle to the march towards development and the eradication of poverty, climate change is today an omnipresent theme within the actions of the WBG. For water management systems projects, the WBG:

- Funds the realization of climate change impact assessments at the global / national, regional (watershed), and individual project scales;
- Seeks to introduce new professional best practices to better integrate uncertainties and climate variability in the design and operation of major water management systems to improve their resilience to climate change;
- Intends to make Climate Change Risk Assessment a mandatory condition to any investment decision (similarly to Environmental and Social Impact Assessment).

2.2 Professional Associations

Among the remarkable and recent actions carried out by major professional associations, we will retain here:

- The WBG/IHA joint initiative for creating the Hydropower Sector Climate Resilience Guide. It has implied a large panel of stakeholders (developers and owners, international financing institutions, consultancies, international and development organisations and academic institutions) and aimed at developing an operational set of guidelines relevant to the hydropower sector on industry good practice in building climate resilience into new and existing projects. The Guide was released in 2019.
- The publication in 2016 of an ICOLD bulletin on "Climate Change, Dams, Reservoirs and Associated Water Resources" [13]. It is worth mentioning that it is the first formal ICOLD technical bulletin (numbered 169) related to climate change issues coming from this almost centenary organization. Its purpose is to assess the role of dams and reservoirs in adapting to the effects of global climate change, determine the threats and potential opportunities posed by global climate change to existing dams and reservoirs, and then recommend measures to mitigate against or adapt to the effects of global climate change.
- The multiplication of the issue of climate change in international professional conferences.

2.3 Papers

An indicator of the rise of the theme of climate change and its impacts in the sector of dams and reservoirs is given by the growing number of papers published in professional journals. The exercise here focuses on the archives of the journals Hydropower and Dams and International Water Power and Dam Construction between 1994 and 2019. The cumulative number of papers is shown in Figure 2. The theme remained quite confidential until the mid-2000s, then became more frequent with an acceleration in 2015 marked by the 21st COP in Paris and the special edition of Water Storage and Hydropower Development for Africa (4 articles).

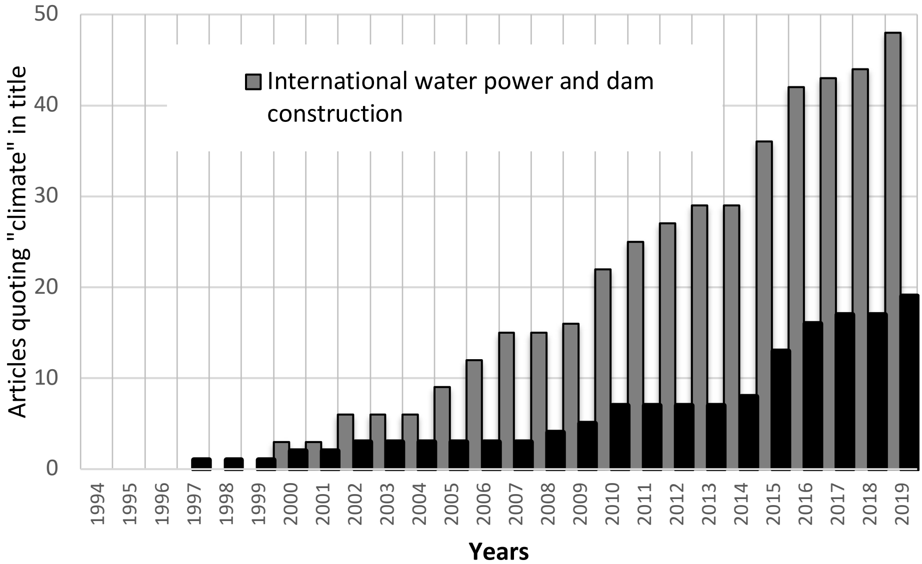

Fig. 2. Cumulative number of articles whose titles include the term 'climate'.

3 Climate stress test: Case Study in Liberia

3.1 Method

The adopted approach for the climate stress test fully complies with the Hydropower Sector Climate Resilience Guide released by IHA in 2019. The IHA Guide has adopted an approach to climate resilience for the hydropower sector, designed to address inherent climate change uncertainty. There are many causes of uncertainty ranging from the complexity of predicting multiple scenarios of future changes with confidence to the lack of necessary data. Such an approach, often referred to as 'bottom-up' approach, proves a valuable alternative to the top-down approaches used in climate risk assessments, the utility of which is often hindered by the lack of high confidence future climate projections derived from General Circulation Models (GCMs) [1].

The approach described in IHA Guide is drawn from the Decision Tree, which is an implementation of general Decision Making under Uncertainty (DMU). It represents the culmination of years of experience in assessing climate and other risks to infrastructure investments and the practice of decision-making under uncertainty generally [14].

The logic of the approach is simple: instead of attempting to use downscaling to predict climate change, which is inherently unpredictable, this approach identifies vulnerabilities to climate change and other factors by exploring the effects of a systematically sampled wide range of changes in climate and other non-climate factors. If vulnerabilities emerge, their level of concern is judged and managed pragmatically based on the specific variables and values that cause the vulnerability [14].

The process of the IHA Guide is shown in Figure 3. The guide consists of six phases, including preliminary requirements, a qualitative assessment of the project climate risks (Phase 1), an initial analysis (Phase 2), a climate stress test (Phase 3), a risk management plan (Phase 4), and lastly the monitoring evaluation and reporting of the results (Phase 5).

As defined by the IHA Guide, the climate stress test (Phase 3) has the 'objective to assess project performance under different possible future climate scenarios in order to support

 https://doi.org/10.1051/e3sconf/202234604004

decision making on resilient design and operation, and to quantify climate risks' [1]. It can be referred as a 'carefully structured multi-variates sensitivity analysis'. It does not restrict the range of climate changes considered to simply the range that global climate models produce, since it is well known that those models do not delimit the true range of uncertainty [14].

A modelling cascade is needed to assess the generation and economic performance of the project under conditions of climate change. A representation of the models that can be used in the stress test is shown in Figure 3. The hydrological model transforms the climatic data into inflow data, which in turn provides the input for the hydropower model. The hydropower model, which typically includes models that capture reservoir and power plant operation, transforms inflow data into generation data. Finally, the economic model transforms the generation data into economics figures.

Initially, the stress test should simulate the hydropower generation and economic performance for the baseline. Then, the stress test assesses the performance for the range of possible climate scenarios.

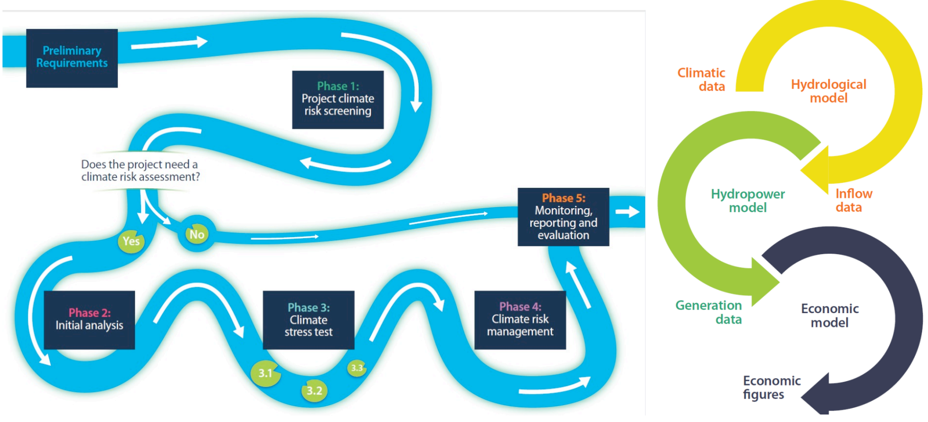

Fig. 3. The process of the Hydropower Sector Climate Resilience Guide (left) and a representation of the models that can be used in the stress test (right) (source: [1]).

In this paper, the stress test does not cover the economic aspects and the outcome is how the project would perform under different possible climate futures based on generation data metrics.

3.2 Study area

The climate stress test is carried out for a large hydropower project located in the St Paul River Basin in Liberia, West Africa. The St Paul River is one of the largest river in Liberia. It has headwater in south-eastern Guinea, then crosses Liberia in a south-westerly direction and discharges into the Atlantic Ocean near Monrovia. The upper part of the basin is densely forested. The middle part is occupied by agriculture-degraded forest and the lower part is an agricultural area with patchy forest presence.

The St Paul River basin has a tropical climate, which is characterized by one wet season between April and November and a marked rainfall gradient with rainfall increasing from upper parts to lower parts of the basin. The rainfall season is largely controlled by the movement of the Inter-Tropical Convergence Zone (ITCZ), which oscillates between the northern and the southern tropics over the course of the year. In contrast to rainfall, temperature and potential evapotranspiration exhibit few variation during the year. The St

Paul River catchment drains an area of 18,276 km² at the Haindi gauging station, which is just downstream the projected dam site.

3.3 Hydrological model

Considering the data scarcity on the study area, a conceptual and parsimonious model was favoured. The rainfall-runoff GR4J [15] was chosen since it has already yielded satisfactory results in West Africa. Using daily basin-wide rainfall/PET data, this model represents, in a conceptual manner, the flow processes in a catchment and makes it possible to simulate runoff at its outlet (here, Haindi gauging station) with a daily time step. The model considers two reservoirs (one production store and one routing store) and has 4 four parameters (*X1* to *X4*) as shown in Figure 4. These parameters need to be calibrated to account for the different sources of runoff and the groundwater exchange term.

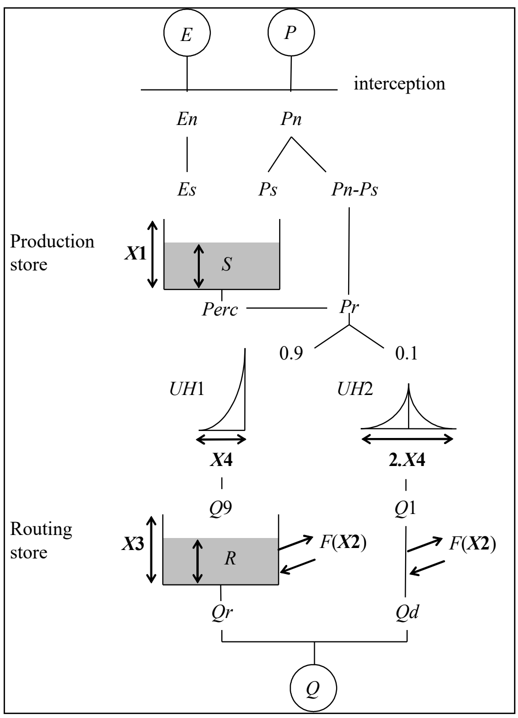

Fig. 4. Principle of the GR4J hydrological model.

3.4 Hydropower model

The main characteristics of the hydropower project come from the previous feasibility studies. In this climate stress test, the HPP scheme is modelled as a run-of-river type one. The available inflows (river inflows minus constant environmental releases) pass through the turbines up to the maximum discharge capacity equal to 420 m³/s, then the flows in excess are discharged through the spillway. The reservoir water level remains constant over the entire simulation. The effective head is in the range 44 – 45 m.

The simulation is run at the daily time step. The hydropower model is supported by the software Mike Hydro Basin edited by the Danish Hydraulics Institute (DHI).

3.5 Data

3.5.1 Hydro-climatic data over the baseline period

Daily discharge data are from the Haindi gauging station (04SP001) operated by the Liberian Hydrological Service since 2012. It has a complete high-quality daily discharge series from April-2012.

Daily rainfall data are from the quasi-global gridded high-resolution (0.05° square grid) rainfall dataset CHIRPS (1981 to date) [16]. Data processing was carried out to derive the basin-wide daily rainfall series (1981-2020). Daily rainfall series at rainfall stations in the study area (above all, Haindi, Piatta, and Nzerekore rainfall stations) were also used to verify the ability of the CHRIPS rainfall dataset to reproduce the rainfall variability over the study area.

Potential evapotranspiration (PET) was estimated on a 0.5°C square grid, using the CRU TS4.0 global climatic database [17]. Since the only data available for calculating PET were temperature data, a formula relying on solar radiation and on mean temperature was selected [18] and performed according to the following equation:

$$PET=(R/28.5) \times [(T+5)/100] \text{ if } T+5 \geq 0, \text{elseif } PET=0 \quad (1)$$

where PET is potential evapotranspiration (mm/d), R the extra-atmospheric global radiation (MJ/m²/d) and T the temperature of the air at 2 m of altitude (°C). R depends on latitude and the Julian day of the year.

3.6 Model calibration and validation

The hydrological model was calibrated for the entire period of overlap between rainfall/PET data and discharge data at Haindi gauging station (April-2012 to September 2020). In order to obtain a successful calibration by using automatic optimization routines, it was necessary to formulate numerical performance indicators that reflect the calibration objectives. The Nash-Sutcliffe (NSE) criterion is as well-known form of normalized least squares objective function. Perfect agreement between the observed and simulated values yields an efficiency of 1, whilst a negative efficiency represents a lack of agreement worse than if the simulated values were replaced with the observed mean values. The NSE criterion is calculated as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{sim,i} - Q_{obs,i})^2}{\sum_{i=1}^{n}(Q_{obs,i} - Q \quad)^2} \quad (2)$$

Where $Q_{sim,i}$ is the simulated flow, $Q_{obs,i}$ is the observed flow and Q is the mean observed flow calculated on the period April-2012 to September 2020.

The NSE criterion was also calculated on the root-square and on the logarithm of the flow, which is more relevant for medium and low flow respectively.

Traditionally, hydrological models are calibrated and then assessed on an independent period (split-sample) to determine their adequacy in simulating streamflow as compared to observations. Here, the period was separated in two periods: April-2012 to December 2016 and January 2017 to September 2019. Each sub-period plays in turn the role of calibration period and validation period. Validation consisted in running the model on the validation period with the parameters optimized on the calibration period.

In both calibration and validation, the first 6 months of simulations were used as a warm-up, to eliminate the influence of initial conditions in the model reservoirs.

Since the maximum discharge hydropower plant capacity is approximately the 40th percentile of the daily inflows (meaning daily inflows are larger that discharge maximum capacity on average 40% of time), the accuracy of the model on the medium and low flows was favored. For this, the model calibration was performed with the objective to maximize the NSE criterion calculated on the root square and the logarithm of the flow.

3.7 Building future climate scenarios

First, the point reference for the climate stress test (baseline) was defined as the 1982-2020 period.

Then, the review of the latest IPCC ensemble of projections from the Coupled Model Intercomparison Project (CMIP5) allowed the building of plausible future climate change scenarios. The review was supported by various sources including the ClimGen [19] country scatter plots produced by the University of East Anglia using the latest IPCC data and he WBG's Climate Change Knowledge Portal [20].

The ClimGen scatter plots for Liberia are shown in Figure 5. These are climate projections for a fixed global warming from 1°C to 4°C above the 1961-1990 baseline period. The changes in annual average temperature and precipitation from the baseline period are given for 21 CMIP5 climate models (coloured, filled symbols). The spread in the projections from the CMIP5 multi-model ensemble is visualized by the shaded brown ellipse.

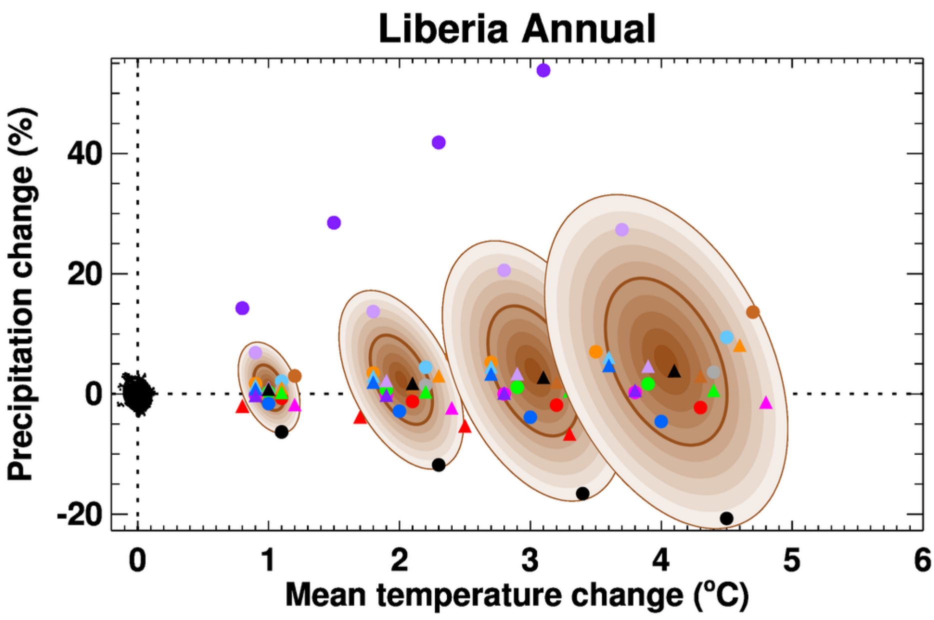

Fig. 5. Projections of national average climate change in Liberia (source: ClimGen).

The WBG's Climate Change Knowledge Portal provides average seasonal anomalies (or changes) of precipitation and temperature for the CMIP5 multi-model ensemble for different future horizons. The 10th, 50th and 90th percentile change values of temperature and precipitation of the CMIP5 ensemble for the time horizon 2060-2079 and the emission scenarios RCP8.5 are shown in Table 1.

Table 1. Projected changes in precipitation and temperature in Liberia (source: [21]).

	J	F	M	A	M	J	J	A	S	O	N	D	An-nual
Change in Temperature (°C)													
RCP8.5													
10^{th}	1.72	1.76	1.56	1.48	1.58	1.73	1.78	1.74	1.71	1.73	1.59	1.66	1.67
50^{th}	2.62	2.56	2.53	2.36	2.33	2.25	2.23	2.25	2.29	2.27	2.45	2.63	2.40
90th	3.69	3.57	3.79	3.88	4.00	3.81	3.61	3.35	3.25	3.33	3.58	3.83	3.64
Change in Precipitation (%)													
RCP8.5													
10th	-168	-43	-24	-30	-30	-18	-14	-25	-17	-15	-16	-26	-22
50th	-1	-4	-6	-4	-3	0	6	3	3	3	18	42	2
90th	117	50	33	22	31	25	25	25	14	24	67	145	28

According to the IHA Guide, these quantiles may be used to achieve a defensible range of plausible future change but the range of applied climate shifts should also extends beyond the typical range of the ensemble of climate model projections to ensure that no vulnerabilities are missed.

The change factors adopted for the stress test are as follows:

- +0°C, +2°C and +4°C in temperature relative to the baseline period.
- -40%; -20%, -10%, -5%, 0%, 5%, 10%, 20% and 40% in precipitation relative to the baseline period.
- The changes in temperature and in rainfall were applied uniformly throughout the year.

A climate scenario was derived for each combination of temperature and rainfall change factors (3 change factors in temperature x 9 change factors in precipitation = 27 climate scenarios).

It has been assumed that the rainfall–runoff relationship existing during the observed time period does not change in the future. This assumption enables the order of magnitude of changes in the hydrological regime resulting from climate change to be assessed.

3.8 Results

3.8.1 Hydrological model

The first results regard the calibration and validation of the hydrological model. The hydrological model has to accurately match the observed data, for not creating significant errors that would bias the prospective hydrological simulations.

Analysis of the fit of the hydrological model (Figure 6) clearly shows that simulated discharges reproduce quite accurately the observed values, although simulated discharges tend to be overestimated for the largest flows. However, this is not an issue since such large inflows will be discharged through the spillway anyway, thus not affecting the reliability of the hydropower calculation. NSE values calculated on root square and logarithm of the flow are over 0.76 in both the calibration and the validation periods.

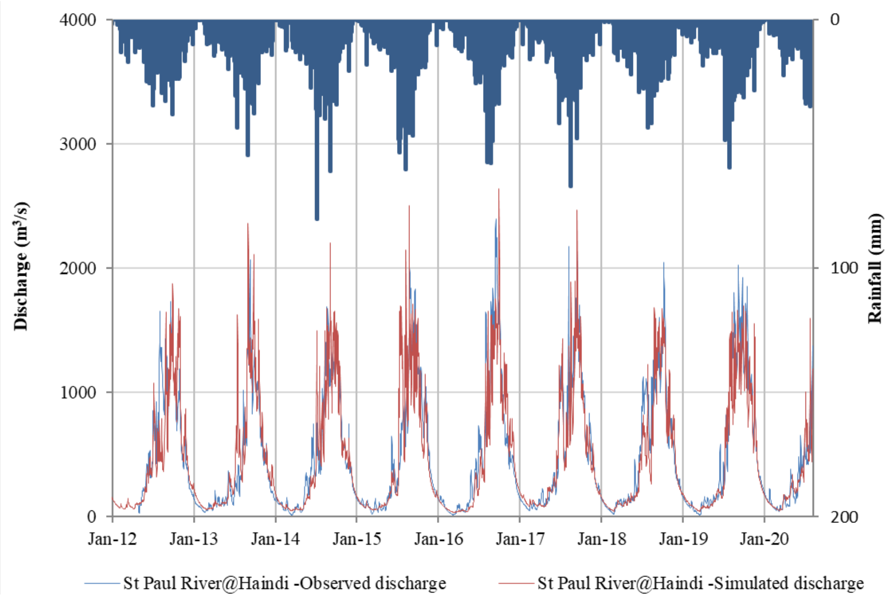

Fig. 6. Comparison of the observed and simulated hydrographs at the Haindi gauging station over the 2012-2020 period.

The hydrological model is thus assumed to be capable of providing inflows simulations for the hydropower model. The hydrological model was first run to simulate the complete series of daily inflows over the baseline period (1982-2020), then for each future climate scenarios (39-year series). The changes in mean annual runoff are shown in Table 2.

The climate scenarios with projected decrease in rainfall and increase in temperature, thus PET, suggest that runoff could be substantially reduced in the future.

The response of the system is more sensitive to the change in rainfall than in temperature. Yet, considering the scenarios with no change in rainfall, the changes in runoff are -9% and -18% for changes in temperature +2°C and +4°C respectively.

Finally, the results show that the response in runoff to a change in rainfall is not linear. This is consistent with previous works showing that the decrease in mean annul discharge of the West Africa region's largest rivers has sometimes been twice the decrease in rainfall for the 1970-2000 drought period.

Table 2. Projected changes in mean annual runoff for each future climate scenarios in reference to the baseline.

	Change in Precipitation (%)								
Change in Temperature (°C)	**-40%**	**-20%**	**-10%**	**-5%**	**0%**	**5%**	**10%**	**20%**	**40%**
0°C	-80%	-40%	-22%	-9%	0%	10%	23%	46%	88%
+2°C	-84%	-51%	-30%	-20%	-9%	2%	13%	36%	81%
+4°C	-87%	-58%	-38%	-28%	-17%	-6%	5%	27%	72%

3.8.2 Hydropower model

Finally, the inflow data provide the input for the hydropower model, which transforms the inflow data into generation data.

The daily series of power generation for the baseline and a given future climate scenario (+2°C, -20% rainfall) are shown in Figure 7 hereafter. Each year of the simulation period is illustrated by a thin grey line while the 10th, 50th and 90th percentiles are illustrated by thick red lines

Given the nature of the hydropower project, the seasonal pattern of the generation is similar to the one of the inflows. In the baseline, the power generation is typically in the range 20-60 MW in low flow season and reaches its maximum (154 MW) between July and November. In the future climate scenario predicting increase in temperature (+2°C) and decrease in rainfall (-20%), the power generation is typically in the range 10-40 MW in low flow season and is at its maximum between August and October.

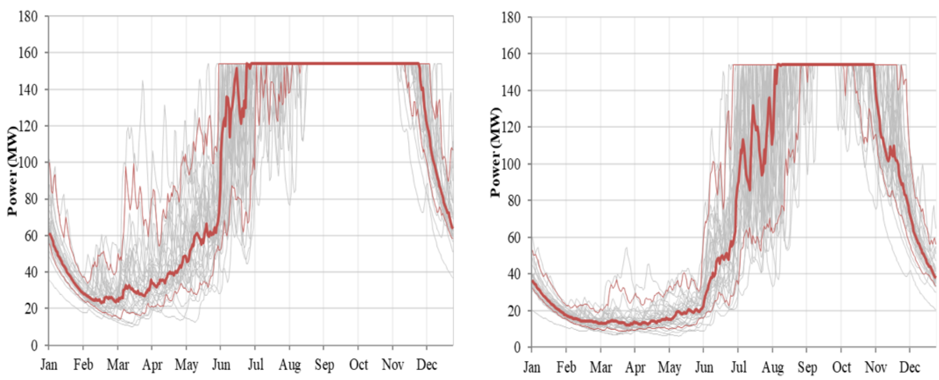

Fig. 7. Daily series of power generation for the baseline (top) and a given future climate scenario (+2°C, -20% rainfall) (bottom).

The effects of the climate change on the hydropower performance of the project are assessed by the following metrics:

- The expected mean annual energy in GWh/year. It is calculated as the average of the power generation over the entire period of simulation.
- The 50th and 90th percentiles of the dry season power generation. Here, the dry season is defined as the period from February to April (3 months). For being a run-of-river type project without any regulation reservoir upstream and characterized by marked seasonal inflows variability to the tropical climate, the generation in dry season is a major issue of the project. Indeed, inflows are the limiting factor to power generation in dry season while the power plant capacity is the limiting factor in wet season.

The results for each climate scenarios are provided as changes in reference to the baseline. The results are shown in Table 3 and Table 4 for the expected mean annual energy and the 50th and 90th percentiles of dry season energy respectively.

As predictable, the expected mean annual energy proves to be sensitive to changes in temperature and even more to changes in rainfall. Depending to the climate state, the performance metric experiences changes from -73% to 25% relative to the baseline. It is worth noting that the performance deficit is more marked than the performance increase for a given rainfall change in absolute value. For example, given a change in rainfall of 20%, the change in mean annual energy would be from -22% to -34% if the change in rainfall is negative and from 5% to 14% if the change in rainfall is positive. Given a +2°C change in temperature the change in rainfall should be between 5% and 10% to balance the negative effect of the increase in PET and maintain the performance of the system.

The generation in dry season is even more sensitive to changes in temperature and rainfall. Depending to the climate state, the performance metrics experience changes from -83% to 85% and from -80% to 48% for the 50th and 90th percentiles respectively. Given a +2°C change in temperature the change in dry season 50th percentile would be -35% if the change in rainfall is -10% and 4% if the change in rainfall is 10%.

Table 3. Changes in expected mean annual energy for each future climate scenarios in reference to the baseline.

	Change in Precipitation (%)								
Change in Temperature (°C)	**-40%**	**-20%**	**-10%**	**-5%**	**0%**	**5%**	**10%**	**20%**	**40%**
0°C	-60%	-22%	-9%	-5%	0%	4%	8%	14%	25%
+2°C	-67%	-28%	-15%	-10%	-5%	-1%	3%	9%	20%
+4°C	-73%	-34%	-21%	-15%	-10%	-6%	-2%	5%	16%

Table 4. Changes in 50th and 90th percentiles of dry season (Feb to April) energy for each future climate scenarios in reference to the baseline.

		Change in Precipitation (%)								
Change in Temperature (°C)	**Percen-tiles**	**-40%**	**-20%**	**-10%**	**-5%**	**0%**	**5%**	**10%**	**20%**	**40%**
0°C	**50th**	-76%	-37%	-21%	-12%	0%	10%	24%	47%	85%
	90th	-71%	-36%	-16%	-8%	0%	8%	16%	28%	48%
+2°C	**50th**	-80%	-52%	-35%	-25%	-17%	-7%	4%	27%	79%
	90th	-76%	-44%	-29%	-22%	-16%	-9%	0%	11%	36%
+4°C	**50th**	-83%	-62%	-46%	-38%	-31%	-21%	-14%	7%	52%
	90th	-80%	-56%	-40%	-36%	-27%	-20%	-16%	-2%	20%

Acknowledgments

The authors acknowledge the Liberian Hydrological Services for providing useful hydro-meteorological data in Liberia.

References

1. International Hydropower Association, Hydropower Sector Climate Resilience Guide (2019)
2. IPCC, Climate Change 2013: The Physical Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (2013)
3. P.J. Mason, Climate variability in civil infrastructure planning, Proceedings of Institution of Civil engineering (2010)
4. G. Mahé, G. The rivers of Africa: Witness of climate change and human impact on the environment, Hydrological Processes, 27, pp. 2105-2114 (2013)

5. C. Taylor, Frequency of extreme Sahelian storms tripled since 1982 in satellite observations, Nature, 544 (2017)
6. Sogreah, Réflexion sur les difficultés d'évaluation du risque hydrologique, Colloque CFBR-AFEID Sécurité des barrages et nouvelle réglementation française (2010)
7. ICIMOD, Impacts of Climate Change on Glacial Lakes (2007)
8. IPCC, Climate Change 2014: Impacts, Adaptation, and Vulnerability, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (2014)
9. B. Hamududu, Assessing climate change impacts on global hydropower, Energies 5, pp. 305-322, (2012)
10. M.T Vliet, Power-generation system vulnerability and adaptation to changes in climate and water resources, Nature Climate Change vol 6, pp. 375-381 (2016)
11. B. Boehlert, Climate change impacts and greenhouse gas mitigation effects on US hydropower generation, Applied Energy 183, pp. 1511-1519 (2016)
12. P.E. Carvajal, Assessing uncertainty of climate change impacts on long term hydropower generation using the CMIP5 ensemble - the case of Ecuador Climatic Change 144, pp. 611-624 (2017)
13. International Commission on Large Dams (ICOLD), Bulletin 169 on Global Climate Change, Dams, Reservoirs and Related Water Resources (2016)
14. World Bank Group, South Asia Investment decision making in hydropower, Decision Tree Case Study of the Upper Arun Hydropower Project and Koshi Basin Hydropower Development in Nepal (2015)
15. C. Perrin, Improvement of a parsimonious model for streamflow simulation, Journal of Hydrology 279, pp. 275-289 (2003)
16. C. Funk, The climate hazards infrared precipitation with stations – a new environmental record for monitoring extremes, Scientific Data, 2 (2015)
17. I. Harris, Version 4 of the CRU TS Monthly High-Resolution Gridded Multivariate Climate Dataset. Scientific Data, 7 (2020)
18. L. Oudin, Which potential evapotranspiration input for a luped rainfall-runoff model? Part 2: towards a simple and efficient potential evapotranspiration model for rainfall-runoff modelling, Journal of Hydrology, 303, pp. 290-306 (2005)
19. T.J. Osborn, Pattern scaling using ClimGen: monthly-resolution future climate scenarios including changes in the variability of precipitation, Climatic Change 134, 353-369 (2016)
20. https://climateknowledgeportal.worldbank.org/