VULNERABILITY TO CLIMATE CHANGE

OF HYDROELECTRIC PRODUCTION SYSTEMS IN CENTRAL AMERICA AND THEIR ADAPTATION OPTIONS

EXECUTIVE SUMMARY

November 2016

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Acknowledgements

We would like to thank the Latin American Energy Organization (OLADE*) for having encouraged this study, for its execution, as well as for their technical and financial support. We thank the Energy and Environment Alliance with Central America (AEA*) for its financial and technical support, and the Advisory Group consisting of the Economic Commission for Latin America (CEPAL*), the Regional Water Resources Committee (CRRH*), the Regional Indicative Planning Task Force (GTPIR*) of the Central American Electrification Council (CEAC*), and the Energy Coordination Unit of the General Secretariat of the Central American Integration System (UCE-SG-SICA*)[1] for all the technical contributions and their participation in workshops throughout the study. We thank the INCLAM-Fundación Bariloche -Climate Focus consortium for preparing this study. And, finally, we would like to express our special thanks to the countries' teams of technical specialists and officials, whose contribution has been invaluable during the course of the study.

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[1] *For their acronyms in Spanish.

Introduction

Central America is one of the most vulnerable regions to the effects of climate change. Located between two continental masses and two great oceans, the region is strongly affected by the El Niño-Southern Oscillation (ENSO) phenomenon, by hurricanes, as well as by temperature and precipitation extremes, which frequently lead to significant droughts and/or rainfall events. Climate change models show that variations in these indicators could become even more pronounced in the region in the coming years. With more than 50% of the electricity generation depending on existing hydroelectric plants by 2015, the region's energy security is heavily dependent on the amount of hydroelectric energy that can be produced and thus on the water flows available in its rivers. In addition, the region still has a significant untapped potential. Consequently, it is critical to determine the potential impacts of climate change on water flows in current and future hydroelectric plants so as to ensure energy reliability and security.

In this context and in response to the request from the countries in the region, the Inter-American Development Bank (IDB) and the Latin American Energy Organization (OLADE*), –with the support of the Energy and Environment Alliance with Central America (AEA*[2]) – undertook the initiative called "*Vulnerability to Climate Change of Hydroelectric Production Systems in Central America and their Adaptation Options*". The aim of this study was to develop and implement a **methodology**[3] for determining the vulnerability of the hydroelectric systems to climate change and identifying possible adaptation measures. This may be considered as the first study conducted on this matter with a comprehensive approach, which emphasizes the need for a replicable methodology. It is a first step in highlighting the importance of incorporating the climate change variable in the design of hydroelectric projects, showing that this is not only possible but also necessary, since water is considered as a primary energy resource that could be significantly affected by climate change.

Methodological Aspects

The geographic area considered in this study includes the continental territory of the seven Central American countries: Guatemala, Belize, El Salvador, Honduras, Nicaragua, Costa Rica and Panama. In the first phase of the study, this territory was distributed into 577 sub-basins for a general analysis and, subsequently, into 38 hydroelectric plants for a country-based analysis. Each sub-basin considered in the region was characterized climatically and hydrologically. The study then evaluated in more detail the hydroelectric power generation for seven of the most important plants in the region (one per country)[4].

Throughout the development of the methodology, hydrological, climate, hydroelectric output, and cost-benefit analysis processing tools were used (and, in some cases, they were created). Climate change information is based on data provided by four climate change models for three emission scenarios (A2,

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[2] *For their acronyms in Spanish.

[3] This methodology is available to the countries and Central American bodies interested in going further into this issue. This tool will be useful for various institutions, including energy planning departments and water resources management agencies. We highlight that, at the time of publication of this study, there are already new climate change scenarios based on the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). These are called the RCP (Representative Concentration Pathways). The methodology used in this study allows to incorporate these new scenarios for future runs of the model.

[4] Chixoy in Guatemala, Mollejón in Belize, Cerrón Grande in El Salvador, El Cajón in Honduras, Centroamérica in Nicaragua, Reventazón in Costa Rica and Bayano in Panamá.

B1 and A1B[5]) and five projection periods (2010, 2030, 2050, 2070, 2090). Climate and hydrometric data[6] were gathered in order to calibrate and validate a rainfall-runoff transformation model[7]. This model is used to characterize the current and future hydrological regime, as well as to measure the variation in extreme events (floods and droughts). It is also used to analyze the effects of the scouring of sediments on total energy produced[8]. The results indicate a potential long-term reduction in the amount of electricity produced in all of the cases analyzed.

The second phase of the study includes an analysis of the potential **economic impacts** of climate change on the electricity sectors for each of the selected plants, depending on the **cost overrun** incurred by each national electricity system so as to meet the additional energy requirements as a result of climate change. The study also analyzes the costs and benefits of the potential adaptation options. In order to evaluate these effects, the following factors have been defined: temporal horizon of evaluations, discount rate, generation expansion and cross-border exchange scenarios, fuel costs and electricity demand growth hypothesis. In order to estimate the economic benefits of adopting each energy policy, it was necessary to make preliminary estimates of the total implementation costs , taking into consideration the impacts of climate change. The generation expansion alternative with the lowest overall costs associated with meeting the projected electricity demand would–at first glance– be the most beneficial. **Given that not all costs associated with these options are taken into account, the results must be interpreted with caution.** With climate change there will also be a considerable degree of uncertainty[9]. The key is to identify mechanisms that allow flexible decision making, based on the best available information.

In addition, to qualitatively measure which sustainability dimensions could be affected by climate change, the study included an analysis based on the application of the energy sustainability indices previously elaborated by OLADE, the Economic Commission for Latin America and the Caribbean (CEPAL*) and the German Technical Cooperation Agency (GTZ) (1997). Likewise, a sensibility analysis was carried out addressing Liquefied Natural Gas (LNG) prices, electricity import and export prices, and the value of the CO^2 emissions avoided, in order to analyze the robustness of the different alternatives considered to meet the projected electricity demand.

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[5] These scenarios are included by the IPCC in the AR4 (CM2.0, MIROC3.2, ECHAM5 and HadCM3). The results from these models were previously submitted to a downscaling and statistic correction process, carried out by E. Maurer. See *Maurer, E., Adam, J., Wood, A. "Climate model based consensus on the hydrologic impacts of climate change to the Rio Lempa basin of Central America." Hydrology and Earth System Sciences.*

[6] Provided by the relevant institutions in each country (e.g. meteorological institutes, ministries or institutions in charge of the environment and/or energy sector, as well as hydroelectric companies involved, etc.).

[7] The study was based on information and data gathered in each country. Its usefulness would increase as more information is included in future runs of the methodology (for example, more historical information from meteorological stations, more advanced climate change scenarios, etc.).

[8] However, it is important to point out that this is an initial analysis of extremes and sediments. There is a need to deepen this analysis in future studies.

[9] The values associated with the different projection periods considered represent the mean value of the results obtained with each of the four global climate change models in which the study is based. As the projection period extends over time, differences between the results of the models increase and become more significant. The Final Report shows an analysis of the deviations obtained for each variable according to the climate change model used and the temporal projection, in order to have a better idea of the **uncertainty** inherent in the models. All climate variables and the estimated water levels and hydroelectric production were calculated for each month of the year, for each climate change model, emission scenario, and projection period considered, in order to assess the possible **seasonal variation** of each variable.

In the third phase of the study, various preliminary adaptation measures were proposed, in order to mitigate the potential impacts of climate change on the amount of electricity generated at each plant.[10]

Throughout the development of the methodology, various workshops were held in the countries, convening some of the main players and technical specialists in the field, in order to discuss different opinions, fine-tune the methodology, share the results and train different technical specialists in undertaking the vulnerability analysis. The workshops gathered staff from the Environment and/or Energy Ministries of the involved countries, as well as operators and planners from the energy sector (public and private), along with staff from various regional bodies, such as the Economic Commission for Latin America (CEPAL), the Regional Water Resources Committee (CRRH), the Regional Indicative Planning Task Force (GTPIR) of the Central American Electrification Council (CEAC), the Energy Coordination Unit of the General Secretariat of the Central American Integration System (UCE-SG-SICA), the Energy and Environment Alliance with Central America (AEA), the Latin American Energy Organization, and the Inter-American Development Bank (IDB).

General Analysis in Central America

Present Conditions: The general analysis[11] shows that Nicaragua, Panama, and especially Costa Rica are currently the countries in the region with the highest rainfall and most water resources per unit area. In terms of temperatures, the highest average values (25°C) can be found in Belize, Nicaragua, and Panama, falling to 24°C in El Salvador, Honduras, and Costa Rica, and up to 23°C in Guatemala. In 2013, all these countries as a whole produced an annual average of approximately 19000 GWh.

Projections: The estimate of hydroelectric output[12] for the initial group of 38 hydroelectric plants shows declines in future output. As regards the general analysis of future projections for the Central American territory, in the first period considered (2000-2019), the model indicates that variations in precipitation and water resources are not significant, but there are slight increases or decreases. For this period, temperature increases by about 0.5°C. In the second period (2020-2039), rain and water resources start decreasing in almost every country and scenario, while temperature increases by about 1°C. Under such circumstances, water resources decrease by 12% on average (A2 scenario[13]). In the third period (2040-2059), the smallest decreases in precipitation and water resources are seen in Guatemala, Costa Rica, and Panama, with water resources declining by about 16%, while in the other countries the decline stands at about 30%. The average temperature increase is 1.6%. For the last two periods of analysis (2060-2079 and 2080-2099), decreases in precipitation and resources are distributed similarly as in the previous periods, with a potential decrease in water resources of up to 55% in some cases, with temperature increases of 3.8°C.

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[10] Also for the countries not to be forced to increase the use of fossil fuels to counteract possible drops in electricity generation based on hydropower.

[11] As a starting point, only data from global climate change models were used, which had been previously submitted to downscaling and statistical correction.

[12] Conducted based on estimates of hydraulic resources from the balance model, and incorporating the series from global climate change models.

[13] Only A2 is considered in this summary. The Final Report also contains results for A1B and B1.

Impact on Production: According to the model, the region's total hydroelectric production will decrease over time, until reaching a potential maximum decrease of 39.5% - or 7500 GWh less generation annually by 2090 -, which is equivalent to the region's total generation in 2008. Even though this is only one of many scenarios, it helps to illustrate the magnitude of the problem that could arise if we do not take measures to adapt to these impacts. The analysis shows that climate change will impact the total energy produced by hydroelectric plants, and their firm capacity, given that the current dry period has become deeper and longer, as we will see in more detail below.

Extreme Events: The analysis shows that droughts will likely become more intense than at present, in terms of both available resources and duration, regardless of the return period considered. On the other hand, the entire region will likely show a similar hydrological regime, with a dry period running from November to April, which implies a significant reduction in hydroelectric production during that period. Even today, that reduction must be offset by alternative energy sources. In the case of floods, the analysis shows a progressive reduction of maximum flows associated with not very high return periods (approximately 2 to 5 years). Meanwhile, for return periods of 10 years or more, water flows increase also progressively and more sharply over time.

Economic Impact: The economic impact assessment shows widely differing results depending on the country, the generation expansion strategy selected, and the discount rate chosen. However, it is worth noting that in none of the countries it represents a negligible figure considering the size of their economies and the needs of their populations. In terms of the ratio Present Value of cost overruns/GDP (2011), the most affected countries could be Honduras, Nicaragua, and El Salvador, with an average value of up to 11% (considering a 4% discount rate). The average supply costs could increase by 7% on average.

The generation expansion strategy that promotes hydroelectric development without restrictions on plant size (HID scenario) is the one that generally entails higher cost overruns as a consequence of the reduction in water flows due to climate change. However, the comparative analysis of the total costs of meeting the demand according to the different expansion alternatives studied (A2 climate change scenario) shows that this does not disqualify it as a valid option for system expansion, given that cost overruns are in many cases compensated for by the advantages offered by the hydroelectric resource.

Case Study Analysis

Below are the most important conclusions derived from the case studies, detailed by country:

Chixoy: According to the analysis, the water flow is expected to vary[14] from -4.6% (2030) to -46.5% (2090). Its current output is 1750 GWh/year, but variations between -8.6% and -44.8% are expected in the projected periods. The current firm capacity of the plant is 279 MW, but may decrease from -15.9% to -44.8% in those periods. The study analyzed the possibility of executing the Serchil hydroelectric

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[14] If a particular scenario is not specified, average variation corresponds to the average obtained for the three scenarios considered (A2, B1 and A1B).

project (although only from a climate change point of view). The model indicates that Serchil would entail an increase in Chixoy's output from 87 (2030) to 81 (2050) GWh/year (A2 emission scenario). It could also entail an increase in firm capacity from 46 to 31 MW, compared to the alternative of not executing the project. The analysis of the economic impact of climate change shows that the cost overruns will range between US$ 67 million and US$ 597 million (depending on the scenario considered and the discount rate chosen), which represents 7% to 66% of the replacement value of the plant.

Mollejón: The water flow is expected to vary from -6.1% (2030) to -35.2% (2090). Its current output is 124 GWh/year, but variations may be expected between -8.6% and -43%. The current firm capacity of the plant is 4 MW, but may decrease from -41.7% to -66.7% during these periods. As an adaptation measure, the study analyzed the potential impact of reforesting the catchment area, compared to the alternative of not reforesting the area.[15] Reforestation would result in an increase in output of 23 to 26 GWh/year and in firm capacity of 2 and 1 MW, in terms of production for the 2030 and 2050 projections using the A2 emission scenario. The economic impact analysis shows that the cost overruns will range between US$ 6.1 million and US$ 66.2 million (depending on the scenario considered and the discount rate chosen), which represents 8% to 88% of the replacement value of the plant.

Cerrón Grande: According to the study, the water flow is expected to decrease from -22.1% (2030) to -58.4% (2090). The annual output is 494 GWh/year, taking into account the influence of the Guajoyo plant, which is currently operating and located upstream. However, decreases between -26% and -64.6 % are expected in those projection periods. The current firm capacity of the plant is 84 MW, but may decrease between -60.7% and -77.8%. Increasing the plant's capacity by including a third turbine (similar to the current ones) has been considered as a possible adaptation measure. Regarding the inclusion of a new turbine in Cerrón Grande, according to this model, the increase in firm capacity would not be significant, while the increase in output would be 3 GWh/year (2050). The economic impact analysis shows that the cost overruns will range between US$ 37 million and US$ 360 million (depending on the scenario considered and the discount rate chosen), which represents 8% to 77% of the replacement value of the plant. [16]

El Cajón: The water flow is expected to vary from -11.3% (2030) to -48.2% (2090). The current output is 1312 GWh/year, but decreases between -14.4% and -51.8 % are expected in those projection periods. The current firm capacity of the plant is 273 MW, but may decrease between -22.2% and -51.6 %. A possible adaptation measure of including a fifth turbine (similar to the current ones) has been considered, and would entail an increase between 6 (2030) and 3 (2050) GWh/year and of 1 and 1 MW for the same time periods. On the other hand, as Honduras is the country in the region with the highest

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[15] The results for this adaptation measure show significant benefits. The cost of reforesting 3% of the contributing watershed is approximately US$ 6 million. Even without internalizing savings from CO2 emissions, the benefits would clearly outweigh these costs.

[16] According to the results obtained from the analysis of adaptation measures, it seems that the best way to protect the energy resources of the Lempa river from climate change is not necessarily to increase the capacity of its plants currently under operation (*Cerrón Grande*, *5 de Noviembre*, *15 de Septiembre*), since they are already well equipped in terms of current hydraulic resources. It would be more profitable to interleave among the current plants, and in stretches of the river still not equipped, plants with a small head and regulation capacity, and with a high level of operational flow, so that they take advantage of the regulation capacity of the plants with reservoirs located upstream.

deforestation rate, of the possibility of reforesting the El Cajón watershed (up to 3%) was also considered, which would increase the plant's output by 21 to 27 GWh/year and the firm capacity by 14 to 16 MW, according to the projections and scenarios already mentioned. The analysis of the economic impact of climate change shows that the cost overruns will range between US$ 77 million and US$ 827 million (depending on the scenario considered and the discount rate chosen), which represents 10% to 110% of the replacement value of the plant.

Centroamérica: The water flow is expected to decrease from -13.1% (2030) to -38.4 % (2090). Its current output is 189 GWh/year, but decreases between -20.8% and -55.6 % are expected in those projection periods. The current firm capacity of the plant is 44 MW, but may decrease between -43.9% and -74.2 % in 2030 and 2090, respectively. The economic impact analysis shows that the cost overruns will range between US$ 12.7 million and US$ 151.2 million (depending on the scenario considered and the discount rate chosen), which represents 10% to 121% of the replacement value of the plant.[17]

Reventazón: The water flow is expected to vary from +2.3% (2030) to -13.9 % (2090). At the time of the study, its output was expected to reach 1578 GWh/year, but may vary between -0.3% and -14.7 % in those projection periods. The current firm capacity of the plant is 217 MW, but may decrease between -8.3% and -23.5 % within the aforesaid periods. As a possible adaptation measure, the study considered increasing the usable head, which would entail an output increase of 214 to 219 GWh/year for 2030 and 2050 projections, respectively, in the emission scenario A2, and an increase in firm capacity of 34 and 46 MW for those projections and that scenario, compared to the alternative of not implementing the measure.[18] The economic impact analysis shows that the cost overruns will range between US$ 22 million and US$ 244 million (depending on the scenario considered and the discount rate chosen), which represents 3% to 32% of the replacement value of the plant.

Bayano: The water flow is expected to vary from -2.5% (2030) to -28.9% (2090). Its current output is 551 GWh/year, but variations are expected between -4.6% (2030) and -37.9% (2090). The current firm capacity of the plant is 127 MW, but may decrease between -4.6% (2030) and -37.9% (2090). As a possible adaptation measure, the study considered the impact of incorporating a new turbine, which would have little influence on the amount of hydroelectric power produced, with a maximum output increase of 3 GWh/year for the 2030 and 2050 projections, emissions scenario A2, while it would have no influence on firm capacity. The economic impact analysis on Bayano shows that the cost overruns will range between US$ 18 million and US$ 205 million (depending on the scenario considered and the discount rate chosen), which represents 3% to 31% of the replacement value of the plant.

Adaptation measures considered for the analysis include structural (increase in installed capacity and usable head, and installation of new waterfall hydroelectric plants), environmental (reforestation), and

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[17] It is not easy to select an adaptation measure for this plant, due to its particular characteristics (for example, storage capacity obtained by the use of a natural lake). However, reforestation measures such as those discussed for Mollejon and El Cajón, would likely achieve similar results in this case.

[18] This assumption is best applied to future hydropower plants, not yet designed or built.

management measures (implementation of watershed management plans, integrated water resource management, use control, and enhanced monitoring networks).[19]

Recommendations

Apart from some previous specific studies, such as "*La economía del cambio climático en Centroamérica: Dos casos de impactos potenciales en la generación de hydroelectricidad*", by ECLAC (CEPAL*), this may be considered as one of the first studies conducted with a comprehensive approach for the purpose of assessing the potential impact of climate change on hydroelectric power generation capacity in the region. Taking into account its pioneering nature, it must be considered as a first step. On the other hand, we must bear in mind that the study is based on the results of ever-evolving climate change models, the precision of which will continue to improve over time. In fact, to the date of publication of this study, new updated scenarios based on the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) had already been developed. The methodology allows to incorporate these new scenarios for future runs of the model.

Below we highlight some recommendations and lessons learned from the study:

1. Regional climate change models: It is necessary to develop regional climate models in order to determine the impacts of and vulnerability to climate change more accurately. The downscaling of global or supra-regional models is insufficient to achieve resolution levels that allow a better identification of impacts and response measures. New versions of regional climate change models are expected, which should be calibrated in Central America, with longer observation and projection periods. These versions will allow to better understand the spatial evolution of the future climate in the region (while always bearing in mind that there will be some level of uncertainty).

2. Information systems: It is necessary to develop, expand and constantly update information systems (on both energy and non-energy data), in order to have sufficiently disaggregated data based on the requirements of vulnerability and adaptation analyses. There should be adequate access to information and previous studies in order to avoid duplicating efforts. Likewise, it is important to recognize the need to develop future socioeconomic scenarios and prospective studies on energy demand growth covering longer periods.

3. Expansion of climate monitoring networks: The region has a low density of climate and hydrometric measurement stations. It is recommended that these networks be expanded and enhanced in order to better understand water availability in the region. Moreover, it is important for the region to advance its protocols for sharing databases and computer tools. This study, for example, could be repeated using more of the information available in the region, which could reduce the uncertainty in the results.

4. Multidisciplinary studies: Due to the expected increase in water demand for other purposes (for example, human consumption, irrigation, industrial, environmental, and other uses), it is recommended

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[19] In general, it is more difficult to quantify costs and benefits of measures with environmental and management components. However, these measures tend to have important benefits, also for other sectors (for example, water availability for irrigation and human consumption, etc.).

that this issue be addressed through multidisciplinary studies to understand the future availability of resources and their allocation to each purpose – including hydroelectricity– more accurately,. In the event of a reduced availability of water resources in the future, it will be necessary to improve the efficiency of systems, and to undertake an integrated management of the resources available.

5. Discount rate: It would be advisable to define basic parameters, values and criteria that enable the evaluation of intervention options in order to meet economic, social and environmental objectives (e.g. cost-effectiveness, efficiency, distributive justice and environmental effectiveness, among others). These objectives should reflect the priorities of the countries and the region. For the Discount Rate, there is a conflict between the traditional short-term economic analysis and the temporal horizons needed to address the potential impacts of climate change.[20]

6. Training: It is essential to ensure ongoing training and updating of human resources in order to keep abreast of the latest developments in terms of the climate change dynamics, the negotiation process and the commitments taken on by the countries, as well as of the evolution of methods, methodologies and tools used in this field to this end.

7. Developing a portfolio of adaptation projects: It is necessary to develop a project portfolio on different sectors in order to implement robust and no-regret actions which anticipate climate phenomena, and which are viable not only as a response to climate change, but also as a contribution to the sustainable development of a country or region. At the national level, the most relevant adaptation measures could be based on several strategies or plans, such as the Intended Nationally Determined Contributions (INDCs), national climate change strategies, national adaptation plans, Nationally Appropriate Mitigation Actions (NAMAs), or sector-specific or watershed plans. It is important for the hydroelectric sector to see the importance (and the opportunity) of working on the matter and implementing the appropriate adaptation measures.

8. Regional and national perspective: Given the characteristics of the Central American region, it is appropriate to carry out actions that are identified, evaluated and implemented at both a national and a regional level, with a broader view and perceptive. Cooperation measures will lead to effectiveness, cost reduction, and the securing of co-benefits that would probably not exist in an isolated analysis. Nevertheless, it is necessary to recognize the difficulty of reconciling a regional approach (with emphasis on the role of interconnections) with national energy policy objectives. It will be necessary to take into consideration the coordination of the different objectives and approaches included in the electricity expansion plans of regional bodies with those of national bodies.

9. Consider climate change at the design level: Finally, and given the potential decrease in future hydroelectric production due to climate change, and taking into account the difficulty in adapting existing plants due to their structural rigidity, it is advisable to implement new integrated regulation systems that allow a better joint operation, develop new hydroelectric plants seeking to restrict water

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[20] It is not feasible to determine what the prevailing investment decisions and available technologies will look like 50 to 100 years from now. However, this temporal horizon is used because, in general, the most significant climate change impacts from the models are appreciated in the long term.

consumption as much as possible through the greatest usable head that is technically and economically feasible, add seasonal storage to compensate for water flow reduction during droughts, etc. It is recommended that the designs of future plants take all these aspects into consideration.

Conclusions

This study has shown that, beyond the evident impact of climate change on the hydroelectric plant development strategy, this does not necessarily disqualify them as a valid option for the expansion of the generation system. In many cases, the attributes of this source might not be offset by the effects of climate change. What is clear from the study though is that the issue is important enough to be worth taking it into account when designing a new hydroelectric plant.

According to the analysis in this study, most catchments in Central America will see a decrease in precipitation, along with the progressive increase in temperature, which would significantly impact water flows, and thus future hydroelectric production. Since drought periods are becoming more extreme, the firm capacity of the plants would continue decreasing. The increase in maximum flood water flows for higher return periods could lead to further damage to the existing infrastructure (impoundments and hydroelectric plants).

However, this tool –along with the work done in Central America– evidence that climate change can be studied and integrated proactively into the most important investments in the region. As a next step, it is highly recommended to introduce a comprehensive and holistic methodological approach in order to study the vulnerability of hydrological resources to climate change. This approach should not only consider the energy field as a system, but should also include all other human activities and ecosystems that depend on the water cycle, so as to incorporate synergies, trade-offs and potential conflicts, in order to identify priorities. This is in the hopes of guaranteeing an adequate management of natural resources in the context of climate change and to ensure their sustainability for the next generations.