BASQUE CENTRE
FOR CLIMATE CHANGE
Klima Aldaketa Ikergai

Climate change impacts on the water services in Costa Rica: a production function for the hydroenergy sector

Elisa Sainz de Murieta and Aline Chiabai

April 2013

BC3 WORKING PAPER SERIES

2013-10

The Basque Centre for Climate Change (BC3) is a Research Centre based in the Basque Country, which aims at contributing to long-term research on the causes and consequences of Climate Change in order to foster the creation of knowledge in this multidisciplinary science.

The BC3 promotes a highly-qualified team of researchers with the primary objective of achieving excellence in research, training and dissemination. The Scientific Plan of BC3 is led by the Scientific Director, Prof. Anil Markandya.

The core research avenues are:

- Adaptation to and the impacts of climate change
- Measures to mitigate the amount of climate change experienced
- International Dimensions of Climate Policy
- Developing and supporting research that informs climate policy in the Basque Country

This Working paper has been produced under the Low Carbon Programme initiative:
http://www.lowcarbonprogramme.org/

The BC3 Working Paper Series is available on the internet at
http://www.bc3research.org/lits_publications.html

Enquiries (Regarding the BC3 Working Paper Series):

Prof. Sérgio H. Faria

Email: sergio.faria@bc3research.org

www.bc3research.org

The opinions expressed in this working paper do not necessarily reflect the position of Basque Centre for Climate Change (BC3) as a whole.

Note: If printed, please remember to print on both sides. Also, perhaps try two pages on one side.

Climate change impacts on the water services in Costa Rica: a production function for the hydroenergy sector

Elisa Sainz de Murieta* and Aline Chiabai*

The case study presented in this section aims to estimate the economic value of the water services used for hydropower in tropical forests in Costa Rica, and to assess the expected economic impact due to climate change. The model developed allows estimating the economic impacts of climate change on the hydroelectric sector, using the association between bio-physical data, technical data related to the plants and economic inputs. A production function is used for this purpose which relates the quantity of water available (runoff) with the energy generated by the selected plants, based on a sample of 40 plants. Results show a significant reduction in the hydropower production in all future scenarios, estimated between 41 and 43% for Costa Rica. This translates in a considerable reduction in the expected revenues of the hydroelectric sector in Costa Rica under all climate change scenarios considered, but with lower reductions in the B1 scenario, which incorporates sustainability criteria. Taking into account future technological changes, the model shows that it would be necessary to double the installed capacity of all plants to get an increase in annual revenue that ranges from 3-18%. With an increase in the installed capacity of about 50%, economic losses would be reduced by 12% in all the scenarios.

Keywords: climate change, hydrological services, hydroelectricity, Costa Rica, economic valuation, production function

JEL Classification: Q23, Q25, Q42, Q51, Q54, Q57

Cite as: Sainz de Murieta, E. and A. Chiabai (2013) Climate change impacts on the water services in Costa Rica: a production function for the hydroenergy sector. *BC3 Working Paper Series* 2013-10. Basque Centre for Climate Change (BC3). Bilbao, Spain.

---

* Basque Centre for Climate Change (BC3), Alameda Urquijo 4 - 4, 48008, Bilbao, Spain.

1 Introduction

The loss of biodiversity is a major problem in nearly every ecosystem on Earth. This loss is accelerating driven by the over-exploitation of natural resources, habitat destruction, fragmentation and climate change (MEA, 2005).

The impact of climate change on biodiversity and ecosystem services (ES) is well documented in the literature and supported by the findings of the recent Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, stating that climate change is already having a strong impact on biodiversity (IPCC, 2007). Even greater impacts on biodiversity are expected in the future (Araújo et al., 2006; Pimm and Raven, 2000; Thomas et al., 2004; Thuiller et al., 2005). By the end of the 21st century, climate change impacts are expected to be the primary cause for biodiversity loss and changes in ecosystem services on a global scale (MEA, 2005).

Global warming in Central America is predicted to cause an increase in temperature and to change the amount and pattern of precipitation. Potential vegetation will shift from humid to dry types and runoff will decrease across the region even in areas where precipitation increases, as temperature change will increase evapotranspiration (Imbach et al., 2012).

The notion of ecosystem services, popularised by the Millennium Ecosystem Assessment (MEA, 2005), provides a cohesive scientific frame for the many mechanisms through which nature contributes to human well-being. ES support (directly or indirectly) human welfare and occur at multiple scales, from climate regulation and carbon sequestration at the global scale, to flood protection, soil formation, and nutrient cycling at the local and regional scales.

This study focuses on terrestrial hydrologic services, analysing how the climate change will affect the provision of water related services. Considering that the hydroelectric sector is directly dependant on hydrological ecosystem services, such as the regulation of water quantity and the reduction of soil erosion and sedimentation (Kaimowitz, 2004), we decided to address the way the effects of climate change on water production will impact the hydroelectric sector in Costa Rica. From a socioeconomic point of view, it is important to highlight the role of the hydroelectric sector, which generated the 78% of the total electricity produced in 2009 in Costa Rica (CEPAL, 2009).

The objective of this study is to estimate the economic value of water production services for hydropower in Costa Rica and to predict the expected changes in hydropower production as well as the economic impact on the revenue estimates of the hydroelectric sector, due to climate change.

2 Theoretical framework

The Millennium Ecosystem Assessment was launched in 2000 seeking to evaluate the consequences of ecosystem change for human well-being and to set up the scientific basis for actions needed to enhance the conservation and sustainable use of ecosystems and their contributions to human well-being (MEA, 2005).

The MEA classifies ecosystem services into four groups: provisioning services such as food, water and timber; regulating services that affect climate, floods, or water quality; cultural services that provide recreational, aesthetic, and spiritual benefits; and supporting services such as soil formation and nutrient cycling.

In this conceptual framework people are integral parts of ecosystems and a dynamic interaction exists between them and other parts of ecosystems, with the changing human condition driving, both directly and indirectly, changes in ecosystems and thereby causing changes in human well-being (MEA, 2005).

Taking the MEA framework as a basis, Brauman et al. (2007) define a specific framework to assess hydrologic services. Figure 1 shows the relationship between both approaches.

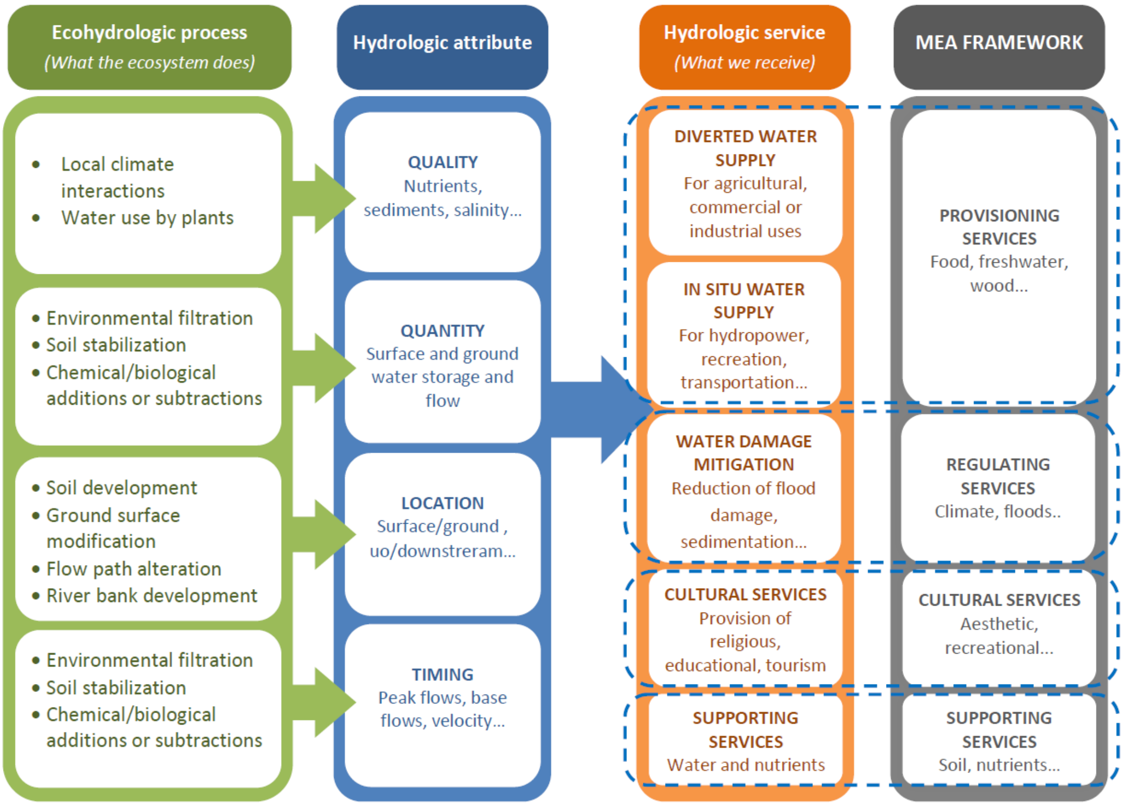

Figure 1. Relationship between MEA general framework and Brauman approach, which shows the complex connection between hydrologic ecosystem services and processes (adapted from Brauman et al. (2007) and MEA (2005)).

Ecohydrologic processes that the ecosystem performs are displayed in the first column of the figure. These processes result in what Brauman et al. (2007) called hydrological attribute, and refers to the quantity, quality, location and regulation of water. Finally, a classification of hydrological services is proposed, from the beneficiary's point of view.

Each of the hydrologic service is determined by the hydrologic attribute, which in turn depends on the ecohydrologic process performed by the ecosystem. Trade-offs are inherent in the supply of hydrologic services and the services can compete with each other and some services will improve at the expense of others. For example, a great quantity of water can be very positive for hydropower, while negative for flood prevention (Brauman et al., 2007).

In this case study, we will follow this classification, as we believe it helps to overcome part of the problems related to the classification of water services and their economic valuation.

The ecological processes defined by Brauman et al. (2007) correspond to the Holdridge life zones (HZ) classification of forests (Holdridge, 1947). This is a simple classification for defining the potential vegetation at each point, depending on climate, altitude and soil type (Figure 2).

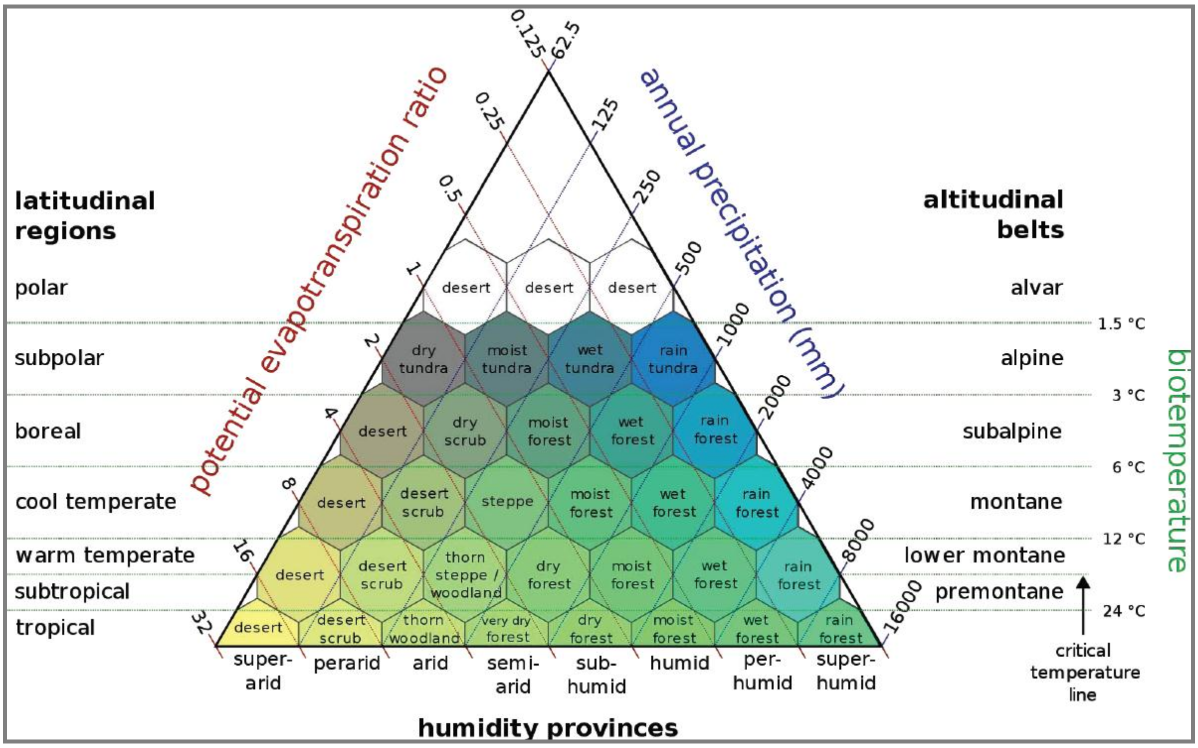

Figure 2. Holdridge life zones classification[1].

---

[1] Figure created by Peter Halasz. Reproduction allowed by "Creative Commons Attribution and ShareAlike"

The MAPSS model (Mapped Atmosphere Plant Soil System), first developed by Neilson (1995), has been adapted to Mesoamerica by CATIE. Through this model vegetation and hydrology data can be obtained, in particular, potential vegetation, evapotranspiration, LAI, and runoff (Imbach et al., 2012). In this case study, the hydrologic attribute described by Brauman et al. corresponds to the production (quantity) of runoff for Costa Rica.

As already mentioned, the hydrologic service addressed in this case study will be the provision of water for hydropower generation. Figure 3 shows how the Brauman classification is applied.

Regarding water services, it has been considered that the most appropriate work-unit is the watershed, since it represents the area for a draining system and there is none -or little- in or outcome flow.

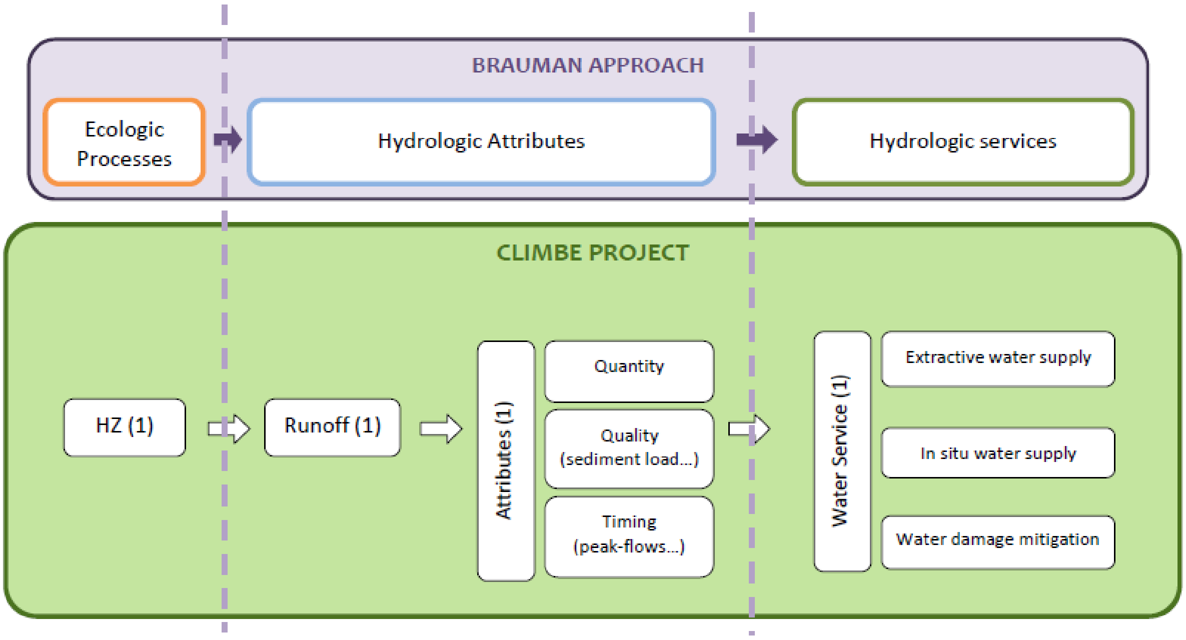

Figure 3. The classification defined by Brauman et al. (2007) applied to the case study. Please, note that the study only considers the hydrologic attribute of runoff quantity and the water supply for hydropower.

3 Economic Model

Economic valuation of water services is a complex issue, which must be carried out with the existing ecological and economic data, that most of the times are scarce.

In this case we will use the productivity method, which is used to estimate the economic value of ecosystem products or services that contribute to the production of commercially marketed goods. It is applied in cases where the products or services of an ecosystem are used, along with other inputs, to produce a marketed good (Núñez et al., 2006).

The productivity method was selected because this is a straightforward case where a hydrologic attribute (runoff quantity) directly affects the cost of producing a marketed good—hydroelectricity. Thus, the increase or loss of the benefits of the hydroelectric sector can be easily related to an increase or reduction of the runoff produced in the watersheds where the plants are located.

This way, the production function can be expressed as a mathematic function where the hydrologic attribute (runoff) relates to the service (hydroelectricity production):

$$Q = Q(X_i, \ldots X_n, W) \tag{1}$$

where Q is the produced electricity or the revenue of the hydropower plant; X are the production factors and W is the hydrologic attribute (runoff).

If we consider a linear production function for equation (1) and we add several production factors, the function is defined by:

$$Q = \beta_0 + \beta_1 X_1 + \ldots + \beta_n X_n + \beta_w W + \mu \tag{2}$$

3.1 The database

We constructed the database from economic data provided by ICE (Instituto Costarricense de Energía), ARESEP (Autoridad Reguladora de Servicios Públicos) and SIEN (Sistema de información Energética Nacional de la Dirección General de Energía), as well as the biophysical data provided by CATIE which have been calculated for the watershed in which each hydroelectric plant is located. Table 1 shows the list of the variables included in the database.

Table 1. List of variables included in the database.

Variables	Description	Units	Provided by
planta	Hydroelectric plant	-	ICE, ARESEP, SIEN
powerkw	Installed power in each plant	KW	ICE, ARESEP, SIEN
storage	Volume of the reservoir	10^3 m^3	ICE, ARESEP, SIEN
caudal	Water volumen going through the plant	m^3/s	ICE, ARESEP, SIEN
caida	Downfall height	m	ICE, ARESEP, SIEN
generation_kwh	Electricity generation. Average value from 1996 to 2009	KWh	ICE, ARESEP, SIEN
revenue_c	Average revenue for each plant from 1996 to 2009	Colones	ICE, ARESEP, SIEN
revenue	Average revenue for each plant from 1996 to 2009	US$	ICE, ARESEP, SIEN

forest_ha	Surface of forested area in the watershed	ha	CATIE
noforest_ha	Surface of non-forested area in the watershed	ha	CATIE
runoff	Average runoff in the watershed	m^3/s	CATIE
dry_hz	Total area of the holdridge zones grouped as DRY	ha	CATIE
moist_hz	Total area of the holdridge zones grouped as MOIST	ha	CATIE
wet_hz	Total area of the holdridge zones grouped as WET	ha	CATIE
rain_hz	Total area of the holdridge zones grouped as RAIN	ha	CATIE
canton	Name of the canton where the plant is located	-	SIEN
province	Name of the province where the plant is located	-	SIEN
river	Main river that feeds the plant	-	SIEN
company	Owner of the hydroelectric plant	-	SIEN

The MAPPS model used by CATIE to estimate runoff can only calculate average values of the runoff produced in each watershed. Figure 4 shows the location of the watersheds considered in the study. This implies that the database built is cross-sectional instead of panel data as time is not included in it.

Regarding the representativeness of the data of the database, the selected 40 hydropower plants represent the 89.9% of the total hydroelectric generation of Costa Rica in 2009 (CEPAL, 2009).

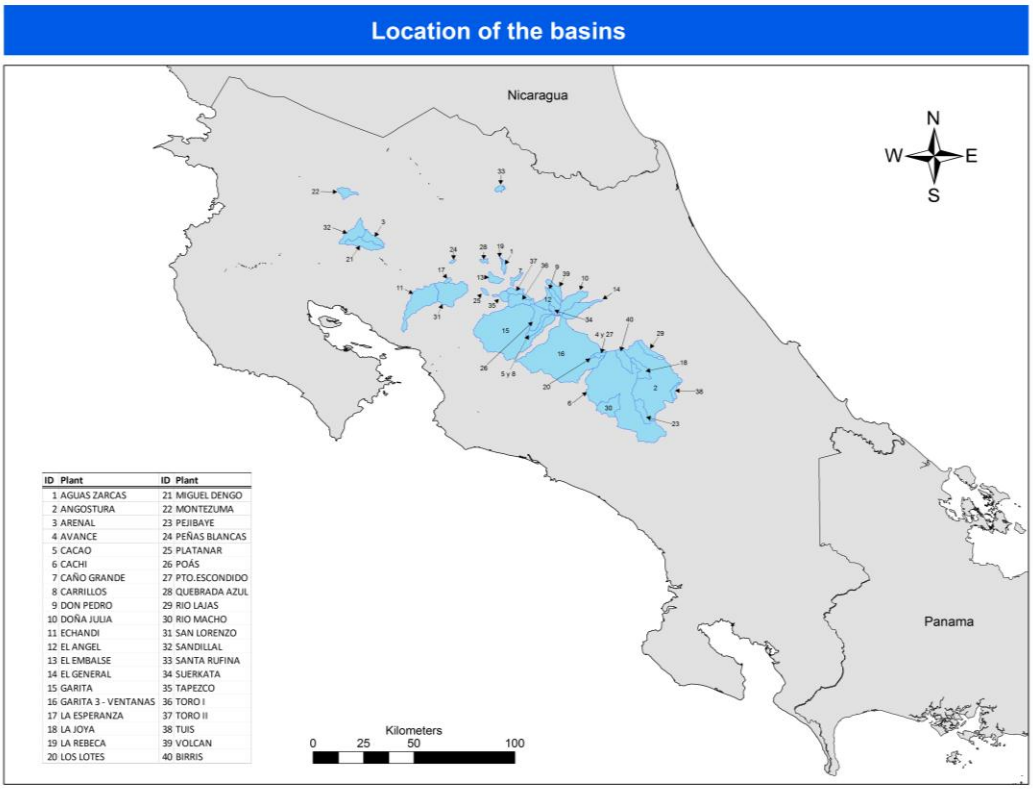

Figure 4. Location of the watersheds included in the database.

3.2 The production function

Following equation Eq. 3, the production function has been built using a subset of the variables indicated in Table 1. To our knowledge, this is the first production function in the literature applied to water provisioning services for the hydroelectric sector.

$$lnQ_{revenue} = \beta_0 + \beta_1 lnX_{runoff} + \beta_2 lnX_{power} + \beta_3 lnX_{fall} + \beta_4 lnX_{storage} + \mu \quad (3)$$

In (3) *lnQ* is the logarithm of revenue per hectare per year, β_0 is the constant term, the *betas* represent the vectors of the coefficients related with the following explanatory variables: runoff per hectare per year (*Xrunoff*), installed power of the hydroelectric plant (*Xpower*), downfall of the plant (*Xfall*), capacity of the reservoir (*Xstorage*), while μ represents a vector of residuals. Explanatory variables are presented in Table 2.

Table 2. List of variables used in the production function.

Variables		**Description**
Dependant variable	logrevenue_ha	Logarithm of the revenue ($) per hectare
Explanatory variables	logrunoff_yr_ha	Logarithm of average runoff in the watershed per hectare per year
	logpowerkw	Logarithm of the Installed power in each plant (KW)
	logcaida	Downfall height (m)
	logstorage	Logarithm of the volume of the reservoir (10^3 m^3)

The results of the production function are presented in Table 3. In all of the cases revenues increase as runoff and the installed power increases, as expected. This means that more runoff and greater installed power translate into bigger revenues for the hydroelectric plant.

The rest of the independent variables –downfall and volume of the reservoir– are not statistically significant, even if we expected an impact of these variables on the energy production. It is worth mentioning however that these two variables had a lot of missing values in the database, and the variability in the volume of the reservoir was very high across the different plants. This is a limitation of the analysis.

Table 3. Results of the production function, dependent variable: revenues per hectare (ln).

logrevenue_ha	**Coef.**	**Std. Err.**	**t**	**P>t**	**[95% Conf. Interval]**	
logrunoff_ha	0.9303	0.0459	20.28	0	0.8330	1.0275
logpowerkw	0.9914	0.0884	11.22	0	0.8041	1.1787
logstorage	0.0347	0.0344	1.01	0.328	-0.0383	0.1078
_cons	-17.8731	1.2600	-14.18	0	-20.5442	-15.2020

Number of obs.	20
F(3, 16)	161.17
Prob. > F	0
R-squared	0.968
Adj. R-squared	0.962
Root MSE	0.32766

As an extension of this analysis, we tried to apply the production function using the logarithm of the electricity generation per hectare as independent variable (see Table 4). The results obtained are very similar to those shown in Table 3 and can be used in future studies to predict the impacts of changes in the production of runoff on the electricity generation. In this study we will only focus on the production function that uses ***revenue*** as dependant variable.

Table 4. Results of the production function, dependent variable: electricity generation per hectare (ln).

loggenerat_ha	**Coef.**	**Std. Err.**	**t**	**P>t**	**[95% Conf. Interval]**	
logrunoff_ha	0.9543	0.0471	20.26	0	0.8544	1.0542
logpowerkw	0.9905	0.0908	10.91	0	0.7981	1.1829
logstorage	0.0266	0.0354	0.75	0.463	-0.0484	0.1016
_cons	-15.6513	1.2944	-12.09	0	-18.3953	-12.9074

Number of obs.	20
F(3, 16)	156.95
Prob. > F	0
R-squared	0.9671
Adj. R-squared	0.961
Root MSE	0.3366

One of the limitations of the proposed production function is that we were not able to include the potential effects of the vegetation types (Holdridge zones). However, we think that these might influence dependent variables, the energy production and related revenues. As the Holdridge zones were amongst the key variables used by MAPSS to model the runoff, we decided to exclude them from our model in order to avoid double counting.

One further limitation is due to the cross-sectional type of data. The model would have benefit from having the two dimensions, the temporal and the geographical dimensions, both in terms of sample size and variability across plants over time.

3.3 Projections under climate change

Three scenarios where considered to estimate the projections in 2100:

- A2: preservation of local identities, population growth and uneven economic growth.
- A1B: rapid economic growth and new technologies. Balance between different types of fuel.
- B1 scenario sustainable approach, with emphasis on global solutions, including greater equality, but without additional climate initiatives.

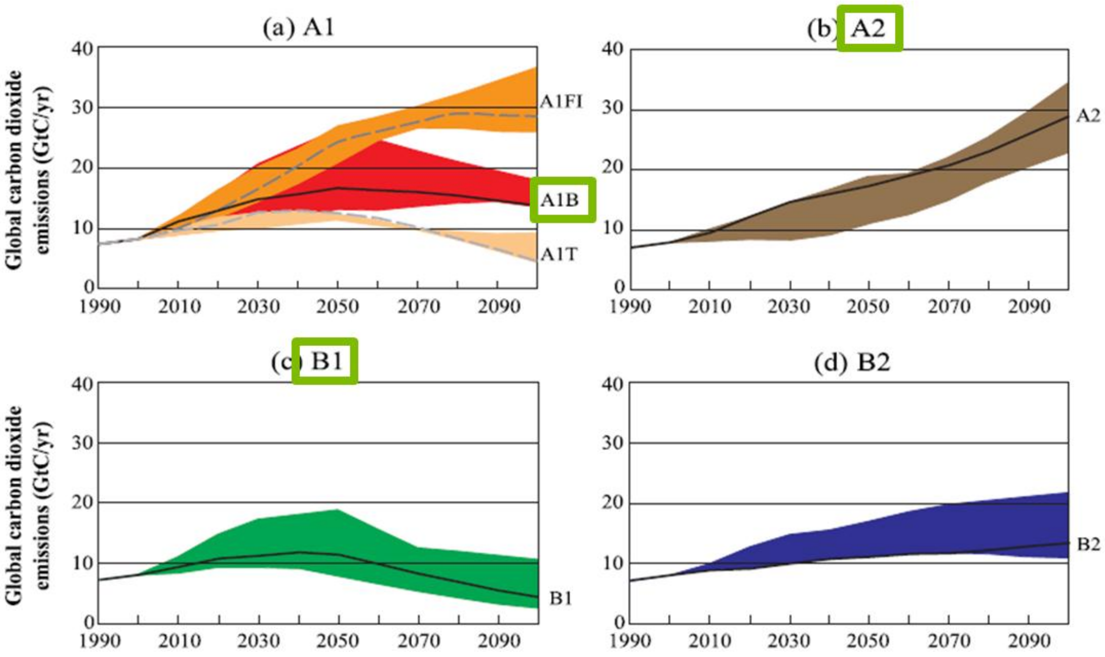

Figure 5. Total global annual CO2 emissions from all sources for the families and six scenario groups. The scenarios are presented by the four families (A1, A2, B1, and B2) and six scenario groups. A1FI (dashed lines), A1T (dashed lines) and A1B in Figure 4a; A2 in Figure 4b; B1 in Figure 4c, and B2 in Figure 4d (IPCC, 2000). The scenarios selected in the study are marked in green.

To carry out the projections, runoff production was estimated under the three selected climate change scenarios (A1B, A2, B1) and the rest of the variables of the production function, related to the characteristics of each hydropower plant, were considered constant over time (Figure 6).

$$lnQ = \beta_0 + \beta_1 lnX_{runoff} + \beta_2 lnX_{power} + \mu \quad (4)$$

To project potential revenues under the different climate change scenarios, we make the assumption that installed power in each plant remains constant in Equation (4), while runoff changes according to the results of the biophysical projections. The values of runoff estimated for baseline and future projections are shown in Figure 6. The decrease of the runoff depends on the plant and the projection.

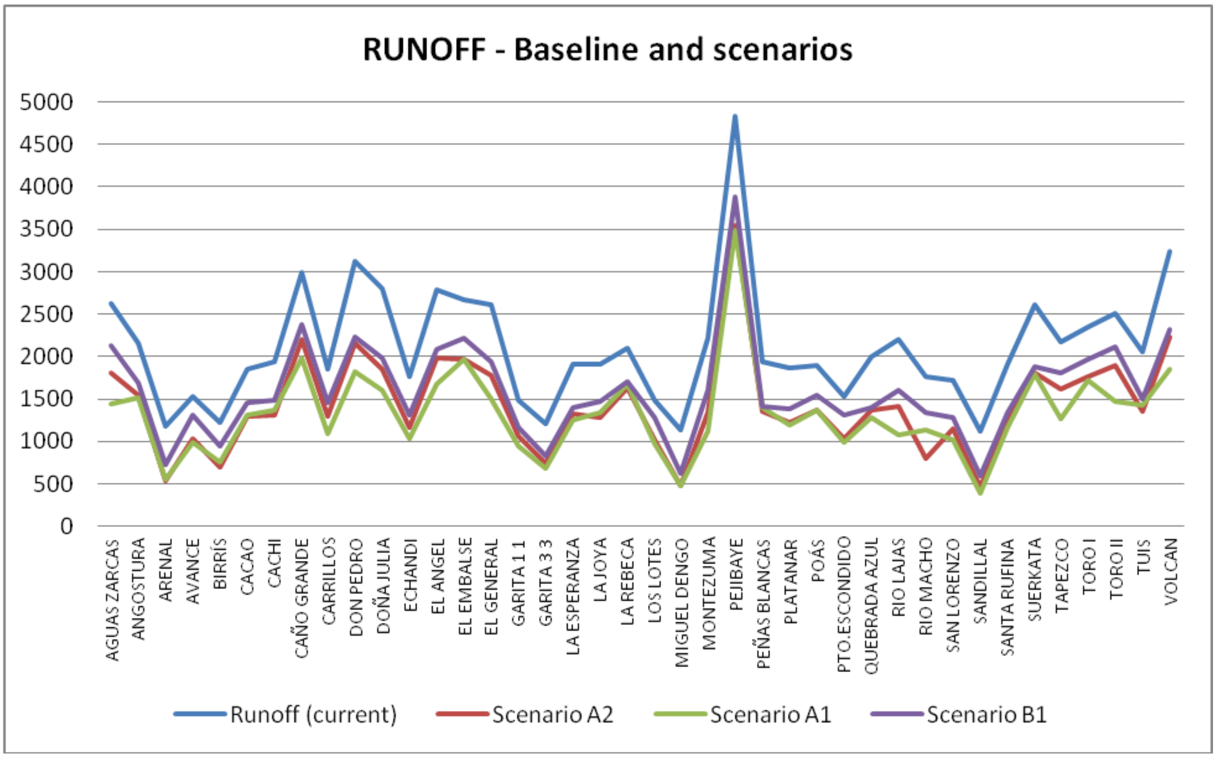

Figure 6. Estimation of runoff (m^3/s) for each hydropower plant and for baseline and future scenarios.

An additional model for the projections was estimated to consider technological improvements. The conditional premise is that technological advances would be translated in an increase of the generation capacity (installed power) of each plant. Thus, we create another series of scenarios in which the installed capacity of each plant increases by 25%, 50%, 70% and 100% at the end of the century.

4 Results

The versatility of the production function estimated from the economic analysis allows showing the results obtained in different ways, as shown in Figure 9. Thus, we can estimate (1) the revenue per hectare per year or (2) the energy generation per hectare per year; we can also get (3) the total economic benefits aggregating the values for Costa Rica or just calculating (4) the economic benefits for each of the plants; besides, economic benefits can be presented for (5) the baseline and (6) the IPCC future scenarios in 2100, as well as the related economic losses; finally, it is possible to estimate the expected economic impacts in 2100 including an approximation to what technological advances could bring (7).

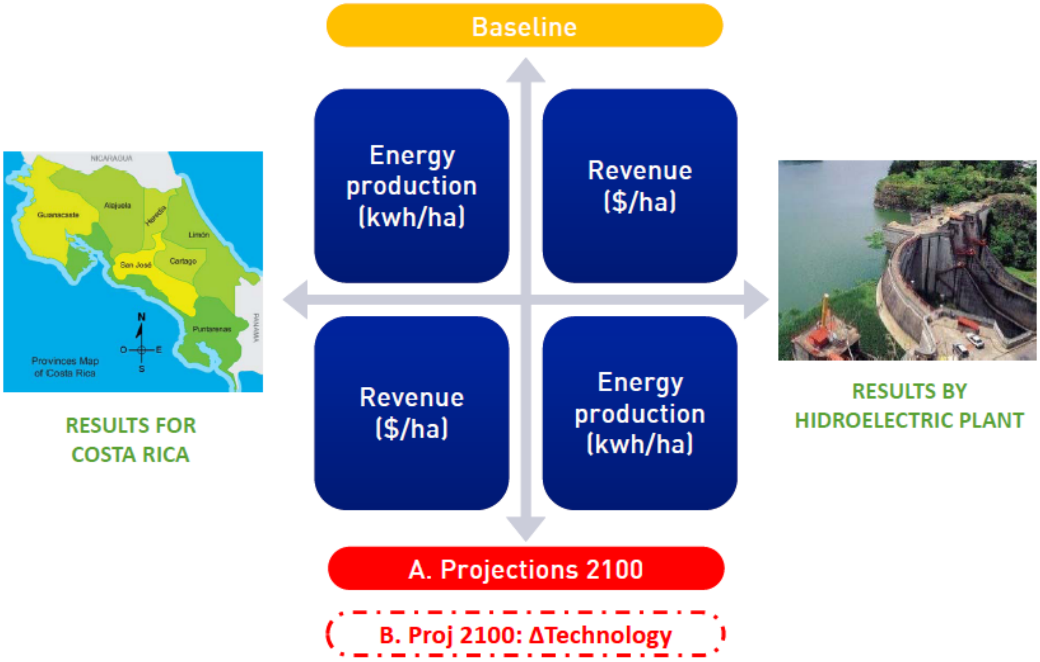

Figure 7. The figure represents different ways in which the production function defined estimates the results.

4.1 Results for Costa Rica

The average monetary value obtained for Costa Rica in the baseline is equal to 2743.80$/ha·year, in terms of total revenue of the plant. This value gets strongly reduced under the three climate change scenarios, although the sustainable oriented B1 scenario represents the lowest loss (Table 5 and Figure 8).

Table 5. Average monetary values ($/ha·year) for Costa Rica (baseline and A2, A1B, B1 scenarios) [2].

	Baseline	Predicted	A2	A1B	B1
Average	2743.80	2179.73	1439.88	1408.56	1608.85
Median	475.97	392.21	257.52	256.92	288.79
Min	2.96	15.43	11.69	9.28	13.00
Max	42105.81	31710.96	22621.83	23262.54	23439.99

---

[2] Note that a predicted baseline value was included in Table 5 and Figure 8 to check how the model replicates the baseline values.

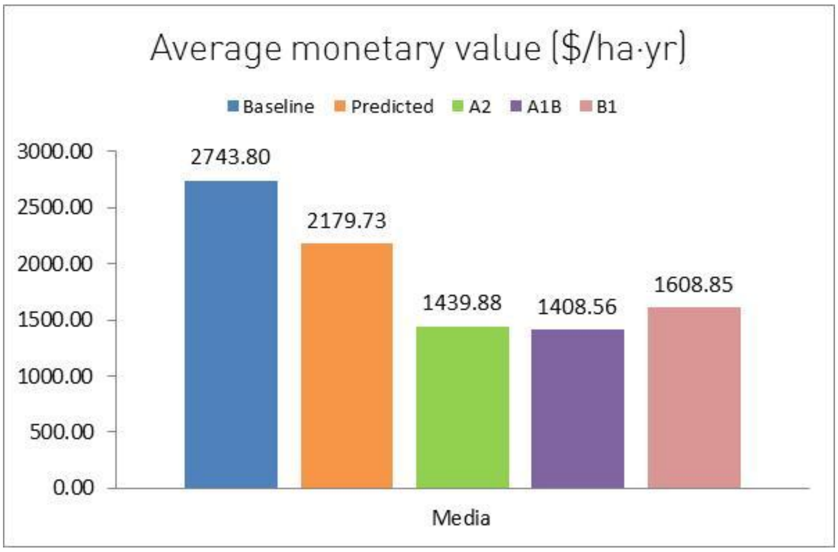

Figure 8. Graphical representation of the average monetary value in terms of revenue($)/ha·yr obtained for Costa Rica.

Aggregate values are calculated by multiplying the values/ha per year by the total hectares considered. If we look at these aggregate values, the estimated losses -in terms of revenue in (M$)/yr- are very significant as well. The losses range from 41% in the scenario B1 to 49% in the A1B (Table 6, Fig. 9).

Table 6. Average aggregated values (M$/year) for Costa Rica (baseline and A2, A1B, B1 scenarios).

	Baseline	Predicted	A2	A1B	B1
Average	1722.69	1368.54	904.03	884.36	1010.11
Median	298.84	246.25	161.68	161.31	181.32
Difference	-	-	-818.66	-838.33	-712.57
Difference (%)	-	-	-48%	-49%	-41%

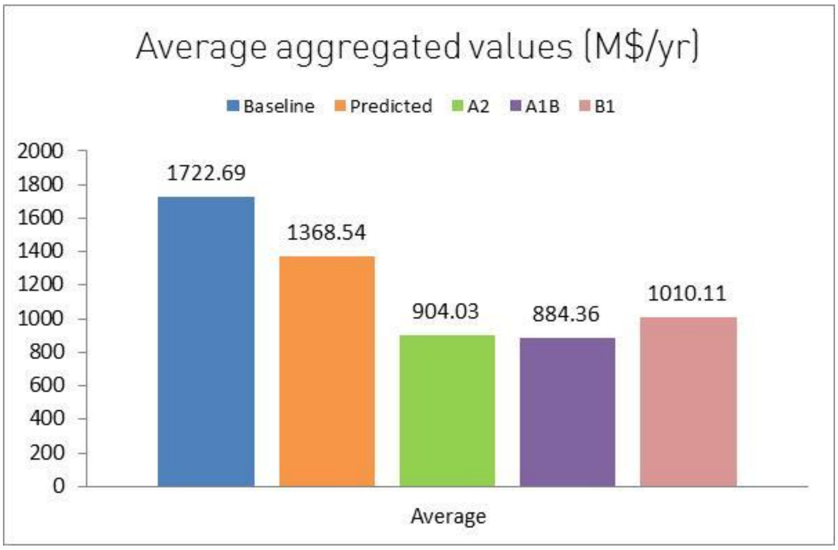

Figure 9. Graphical representation of the average aggregated value obtained for Costa Rica (M$/yr).

4.2 Results for two plants in the Volcánica Central Talamanca Corridor

As an example of the results that can be obtained by hydroelectric plant we selected two plants on the Volcánica Central Talamanca Corridor, La Joya and Rio Lajas. La Joya, managed by the public company ESPH, has an installed power of 50MW and provided more than 250.000MW in 2009. Río Lajas, run by a private company of the same name, generated 54.000MW in 2009, with an installed power of 11MW.

In this case, the results show the same tendency as in the previous case: important losses occur under the three scenarios of climate change and this loss is always lower under the B1 sustainably oriented one (Table 7 and Figure 10).

Table 7. Average monetary values ($/ha·year) for La Joya and Rio Lajas (baseline and A2, A1B, B1 scenarios). The net and porcentual differences between the baseline and each of the scenarios is also shown.

Plant	Value	Baseline	Predicted baseline	A2	A1B	B1
LA JOYA	Average	180.03	220.21	152.01	158.49	164.84
	Difference	-	-	-28.02	-21.54	-15.19
	Difference (%)	-	-	-16%	-12%	-8%
RIO LAJAS	Average	1321.94	1182.09	779.93	599.49	815.03
	Difference	-	-	-542.01	-722.45	-506.91
	Difference (%)	-	-	-41%	-55%	-38%

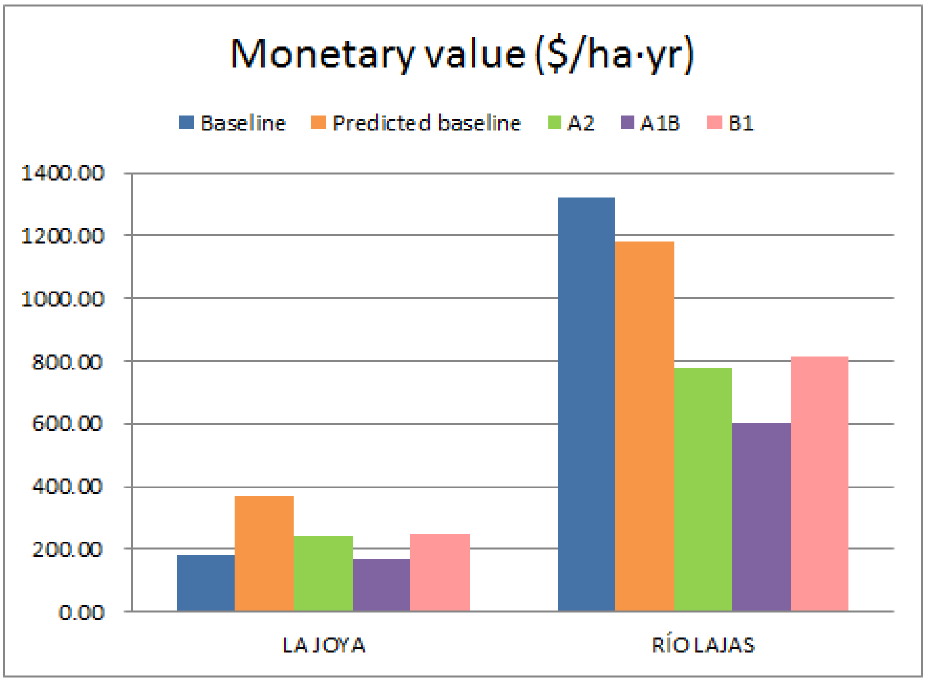

Figure 10. Graphical representation of the average monetary value in terms of revenue($)/ha·yr obtained for La Joya and Río Lajas.

As shown in Figure 10, the values per hectare for La Joya are much lower than the ones for Río Lajas, even though if the first produces much more electricity. This is due to the big extension of the watershed that feeds La Joya plant that almost reaches 90.000 ha, versus 3.367ha in the case of Río Lajas.

If we consider the aggregated benefits per year, these are much higher for La Joya, as expected (see Table 8 and Figure 11). The potential decrease in the total revenues under climate change is higher for Río Lajas, while this reduction is lower for La Joya. In both cases, impacts on scenario B1 are lower than in A2 and A1B.

Table 8. Average aggregated values (M$/year) for La Joya and Rio Lajas (baseline and A2, A1B, B1 scenarios). The net and porcentual difference between the baseline and each of the scenarios is also shown.

Plant	Value	Baseline	Predicted baseline	A2	A1B	B1
LA JOYA	Average	16.13	19.72	13.62	14.20	14.76
	Difference	-	-	-2.51	-1.93	-1.36
	Difference (%)	-	-	-16%	-12%	-8%
RIO LAJAS	Average	4.45	3.98	2.63	2.02	2.74
	Difference	-	-	-1.83	-2.43	-1.71
	Difference (%)	-	-	-41%	-55%	-38%

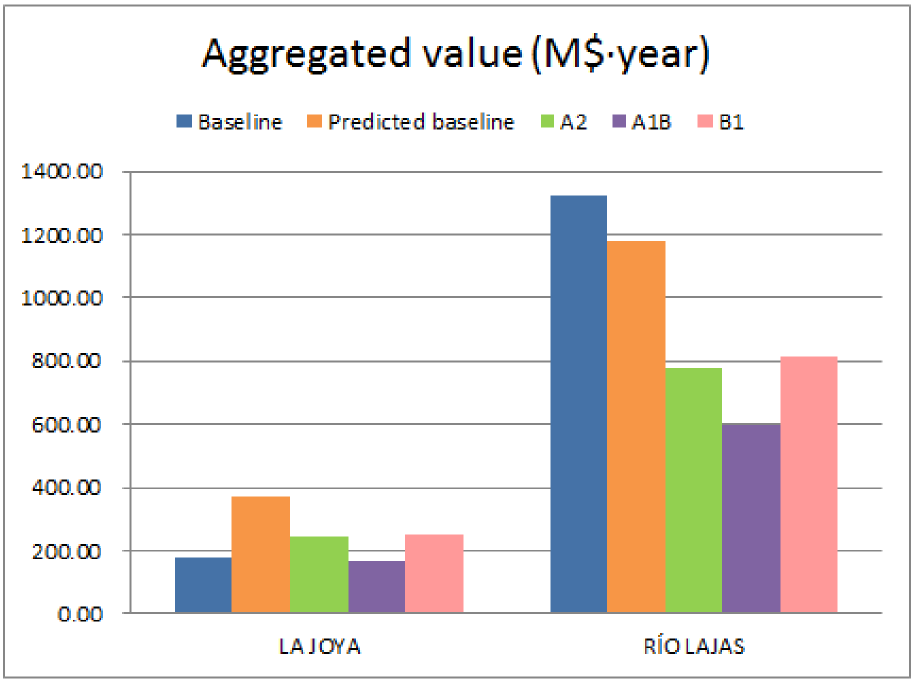

Figure 11. Average aggregated value in terms (M$/yr) obtained for La Joya and Río Lajas.

4.3 Results considering technological advances

Taking into account technological advances is not an easy task due to the great uncertainty that exists about what could be developed by 2100. In this case study we define a simple approach to this advances, considering that the effect of technology would be the increase of the generation capacity of the plants, even if there were no changes on the dam or the reservoir.

To carry out this approach, we estimated changes in the capacity of the plants for each of the scenarios. The aggregated values (M$/yr) obtained are shown in Table 9 and represented in Figure 12.

Table 9. Average aggregated values (M$/year) Costa Rica considering an increase in the generation capacity of the plants due to technological advances (baseline and A2, A1B, B1 scenarios).

Technological scenario	Installed power (MW)	Baseline	A2	A1B	B2
	Actual Capacity	1722.69	904.03	884.36	1010.11
Option 1	**Power + 25%**	-	1132.61	1107.97	1265.52
Option 2	**Power + 50%**	-	1361.66	1332.03	1521.45
Option 3	**Power + 75%**	-	1591.10	1556.49	1777.82
Option 4	**Power + 100%**	-	1820.88	1781.27	2034.56

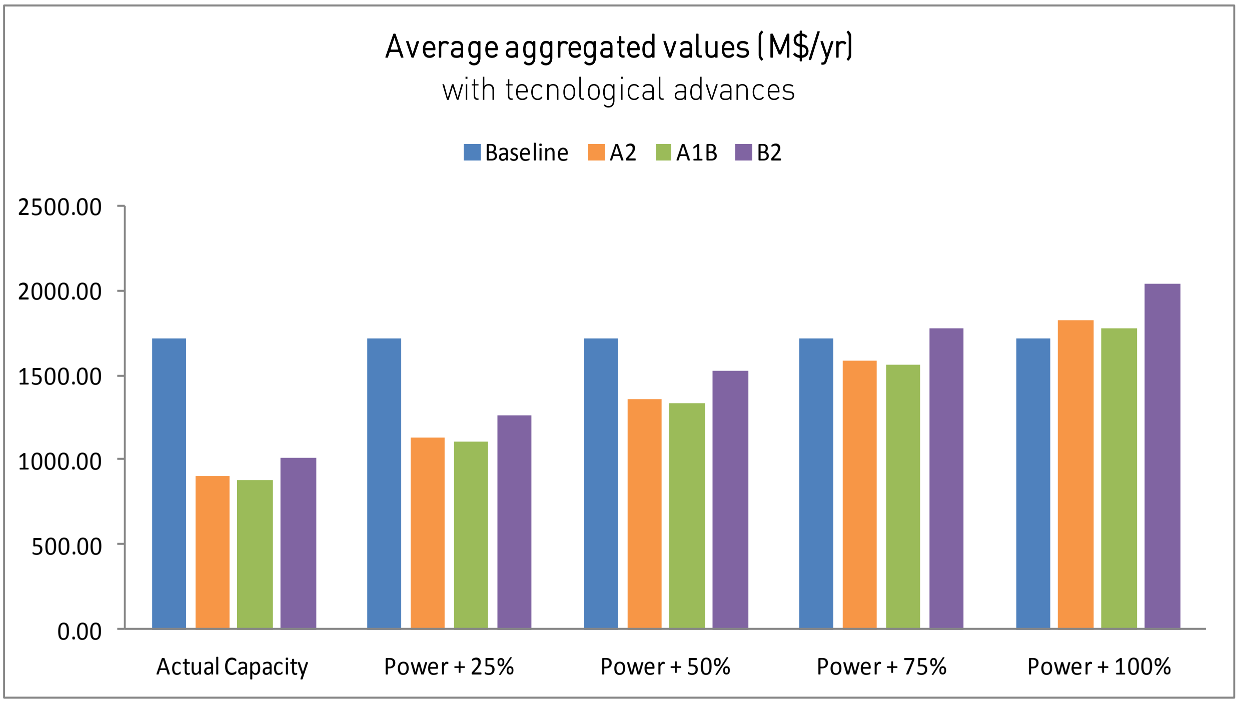

Figure 12. Average aggregated value (M$/yr) for different electricity production capacities in Costa Rica.

Table 10. Porcentual difference between climate change scenarios and baseline for each of the technological scenarios in Costa Rica. Based on Table 6. Average aggregated values (M$/yr) for Costa Rica.

Installed power (MW)	Baseline	A2	A1B	B2
Actual Capacity	-	-47.5%	-48.7%	-41.4%
Power + 25%	-	-34.3%	-35.7%	-26.5%
Power + 50%	-	-21.0%	-22.7%	-11.7%
Power + 75%	-	-7.64%	-9.65%	3.20%
Power + 100%	-	5.7%	3.4%	18.1%

As observed in the tables and graph above, the revenue losses due to climate change will still be considerable and only if installed power doubles we can see an increase in the revenue for scenarios A2 and A1B. Scenario B2 provides a small increase of the revenue already if we raise the installed power in 75%.

5 Conclusions

The case study presented in this section aims to estimate the economic value of the water services used for hydropower in tropical forests in Costa Rica, and to assess the expected economic impact due to climate change on the revenues of the hydroelectric sector as a result of the decreased projected runoff. A sample of 40 plants has been constructed for this purpose. The methodology is based on the production function which relates the quantity of water available (runoff) with the energy generated by the selected plants. Changes in the energy production have been then modelled using the production function under different future IPCC scenario.

The model developed allows to assess the economic impacts of climate change on the hydroelectric sector, using the association between bio-physical data, technical data related to the plants (installed power, downfall height, volume of the reservoir, etc.) and economic inputs (in terms of revenues produced by each plant).

Results show a significant reduction in the hydropower production in all future scenarios, estimated between 41 and 43% for Costa Rica. This translates in a considerable reduction in the expected revenues of the hydroelectric sector in Costa Rica under all climate change scenarios considered (A2, A1B, B1). The reduction is however lower in the B1 scenario, which incorporates sustainability criteria and the impact is greater on the scenarios of group A. Although most revenue reduction would occur in the A1B scenario, the results are very similar in A2. This shows that even following a more sustainable path of development there will be losses, but at least these can be reduced. It is important to notice that the expected impacts can be quite different from plant to plant, depending on the projected decrease of runoff in the respective watershed.

If we do a simple exercise to introduce the effect of technological advances in plant performance, we obtain that it would be necessary to double the installed capacity of all plants to get an increase in annual revenue that ranges from 3-18%. With an increase in the installed capacity of about 50%, economic losses would be reduced by 12% in all the scenarios.

The model developed is, to our knowledge, the first production function applied to water provisioning services and related economic revenues for the hydroelectric sector. It offers a tool that can be easily adapted to other geographical contexts, or to assess the impacts on specific hydrologic plants in Costa Rica.

One of the strengths of this study is the close relationship between biophysical data and modelling, and economic analysis. However, we must be aware of the uncertainty linked to climate and ecological models and that this uncertainty will also affect economic modelling.

Another limitation is that in the construction of the database we couldn´t incorporate annual production data (annual runoff and electricity). Also, some of the variables that we judged originally to have included (such as downfall height, area of the watershed or vegetation type) couldn´t be finally considered due to missing information by plant. In order to properly calibrate the model, the database should be complemented with some additional data and variables, already identified in the framework of the present work. In any case, we believe the three variables used (runoff, power and storage) are representative, as the calibration of the model is acceptable even with a limited number of variables and plants. Further research should also incorporate data on an annual basis in order to improve and calibrate the production function used.

Finally, we should also notice that the estimated economic impacts are due solely to the effect of a change in the provision of water and does not incorporate other effects such as changes in energy prices, the country's economic growth, and others. We believe that the economic impacts related to runoff are well defined, but additional changes in other socioeconomic variables could both mitigate or exacerbate the effects of climate change.

References

Araújo, M.B., Thuiller, W., Pearson, R.G., 2006. Climate warming and the decline of amphibians and reptiles in Europe. J. Biogeogr. 33, 1712–1728.

Brauman, K.A., Daily, G.C., Duarte, T.K., Mooney, H.A., 2007. The Nature and Value of Ecosystem Services: An Overview Highlighting Hydrologic Services. Annu. Rev. Environ. Resour. 32, 67–98.

CEPAL, 2009. Centroamérica: estadísticas del subsector eléctrico.

Holdridge, L.R., 1947. Determination of World Plant Formations From Simple Climatic Data. Science 105, 367–368.

Imbach, P., Molina, L., Locatelli, B., Roupsard, O., Mahé, G., Neilson, R., Corrales, L., Scholze, M., Ciais, P., 2012. Modeling Potential Equilibrium States of Vegetation and Terrestrial Water Cycle of Mesoamerica under Climate Change Scenarios*. J. Hydrometeorol. 13, 665–680.

IPCC, 2000. Emission Scenarios: A Special Report of IPCC Working Group III. Cambridge University Press, Cambridge, UK.

IPCC, 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK.

Kaimowitz, D., 2004. Useful myths and intractable truths: the politics of the link between forests and water in Central America, in: Bonell, M., Bruijnzeel, L.A. (Eds.), Forests, Water and People in the

Humid Tropics: Past, Present and Future Hydrological Research for Integrated Land and Water Management. Cambridge University Press, pp. 86–98.

MEA, 2005. Ecosystems and Human Well-Being: Biodiversity Synthesis. World Resources Institute, Washington D.C., USA.

Neilson, R.P., 1995. A Model for Predicting Continental-Scale Vegetation Distribution and Water Balance. Ecol. Appl. 5, 362.

Núñez, D., Nahuelhual, L., Oyarzún, C., 2006. Forests and water: The value of native temperate forests in supplying water for human consumption. Ecol. Econ. 58, 606–616.

Pimm, S.L., Raven, P., 2000. Biodiversity: Extinction by numbers. Nature 403, 843–845.

Thomas, C.D., Cameron, A., Green, R.E., Bakkenes, M., Beaumont, L.J., Collingham, Y.C., Erasmus, B.F.N., de Siqueira, M.F., Grainger, A., Hannah, L., Hughes, L., Huntley, B., van Jaarsveld, A.S., Midgley, G.F., Miles, L., Ortega-Huerta, M.A., Townsend Peterson, A., Phillips, O.L., Williams, S.E., 2004. Extinction risk from climate change. Nature 427, 145–148.

Thuiller, W., Lavorel, S., Araújo, M.B., Sykes, M.T., Prentice, I.C., 2005. Climate change threats to plant diversity in Europe. Proc. Natl. Acad. Sci. U. S. A. 102, 8245–8250.

BC3 WORKING PAPER SERIES

Basque Centre for Climate Change (BC3), Bilbao, Spain

The BC3 Working Paper Series is available on the internet at the following addresses:

http://www.bc3research.org/lits_publications.html

http://ideas.repec.org/s/bcc/wpaper.html

BC3 Working Papers available:

2012-10 Iker Etxano, Eneko Garmendia, Unai Pascual. David Hoyos, Maria-Angeles Diez, José A. Cadiñanos and Pedro J. Lozano: *Towards a Participatory Integrated Assessment Approach for Planning and Managing Natura 2000 Network Sites*

2012-11 Luis M. Abadie and José M. Chamorro: *Valuation of Wind Energy Projects: A Real Options Approach*

2012-12 Helen Ding and Paulo A.L.D. Nunes: *Modeling the Links between Biodiversity, Ecosystem Services and Human Wellbeing in the context of Climate Change: Results from an Econometric Analysis on the European Forest Ecosystems*

2012-13 Helen Ding, Anil Markandya and Paulo A.L.D. Nunes: *The Economic Impacts of Biodiversity Policy for Improving the Climate Regulating Services Provided by EU Natura 2000 Habitats*

2012-14 Martin-Ortega, J. E. Ojea and C. Roux. *Payments for Water Ecosystem Services in Latin America: Evidence from Reported Experience.*

2013-01 Samuel Bobbino, Héctor Galván and Mikel González-Eguino: *Budget-Neutral Financing to Unlock Energy Savings Potential: An Analysis of the ESCO Model in Barcelona*

2013-02 Agustin del Prado, Karlos Mas, Guillermo Pardo and Patricia Gallejones: *Development of a new modelling framework to estimate the C footprint from Basque dairy farms*

2013-03 Roger Fouquet: *Long Run Demand for Energy Services: the Role of Economic and Technological Development*

2013-04 David Heres, Steffen Kallbekken and Ibon Galarraga: *Understanding Public Support for Externality-Correcting Taxes and Subsidies: A Lab Experiment*

2013-05 Ibon Galarraga, Luis María Abadie and Alberto Ansuategi: *Economic Efficiency, Environmental Effectiveness and Political Feasibility of Energy Efficiency Rebates: the Case of the Spanish Energy Efficiency "Renove" Plan.*

2013-06 Alexander Golub, Oleg Lugovoy, Anil Markandya, Ramon Arigoni Ortiz and James Wang: *Regional IAM: Analysis of Risk-Adjusted Costs and Benefits of Climate Policies*

2013-07 Luis M. Abadie, Ibon Galarraga and Dirk Rübbelke: *Evaluation of Two Alternative Carbon Capture and Storage Technologies: A Stochastic Model*

2013-08 Ibon Galarraga and Josu Lucas: *Economic Evaluation of Energy Efficiency Labelling in Domestic Appliances: the Spanish Market*

2013-09 Daniel Nachtigall and Dirk Rübbelke: *The Green Paradox and Learning-by-doing in the Renewable Energy Sector*

2013-10 Elisa Sainz de Murieta and Aline Chiabai: *Climate change impacts on the water services in Costa Rica: a production function for the hydroenergy sector*