Effects of Climate Change on Hydropower Production Efficiency in Southern Africa

By

Joao Mutondo

International Center for Water Economics and Governance in Africa (IWEGA)

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1. Introduction

Hydropower has been recognized as a sustainable source of energy as it is environmentally friendly (nonpolluting source of energy), has low operating and maintenance cost and technology that offers reliable and flexible operation, and its operating efficiency increases along with long life. Due to the above features, the production of hydropower is expected to grow in developing countries and especially in Sub-Saharan African region, where there is over 400 gigawatts of undeveloped hydro potential.

Despite the existing potential of increasing hydropower production in Sub-Saharan Africa (SSA), the variability of availability of water resources might limit hydropower production in this region. It is important to note that water resources and their availability vary greatly both spatially and temporally across the SSA. This variation is affected mainly by erratic rainfall partly explained by the occurrence of El Nino and La Nina events from which the Southern Africa Region is dramatically impacted by these occurrences.

Additionally, most parts of SSA receive large amounts of solar radiation, resulting in warm to high temperatures, which contributes to an increase in evaporation rates. High evaporation rates cause significant loss of water from surface water bodies. It is estimated that 80% of the rain falling over Africa returns to the atmosphere through evaporation (Shahin, 2002). The combination of highly seasonal rainfall and high evaporation rates results in most rivers drying up during the dry season, which limits the amount of water readily and easily available for hydropower production and other uses.

Moreover, the population of Southern African (SA) countries is increasing at an increasing rate. This has placed pressure in the existing water resources through an increasing demand for drinking water and for economic activities such as irrigated agriculture. Therefore, the planning and design of new hydropower infrastructure in SA should consider a number of variables such as the increase in demand for water from household and industrial consumption and other economic activities such as irrigation, recreation, fishing as well as highly variable climate.

The limited sustainable management of water resources is regarded as one of the main constraints of economic and social development in the long run in many regions of the world including the SA. Water shortage is becoming a common and prevalent issue on the political agenda of different countries. The water related problems will however be intensified by an ongoing pollution of the available water resources.

Any serious solution of the world water crisis will not only consist of additional financial resources transferred to the developing countries for the development of water infrastructures such as hydropower but in the first place will have to find new ways to balance regional water supply and water demand. Supply and demand management requires a better understanding of the trends of the main drives influencing the demand and supply of water as well as the level of water use efficiency among the competing sectors. Therefore, this study assesses the effects of climate change on hydropower production efficiency and fish production profits in SA. The case studies will be concentrated in Kariba, Kafue and Cahora Bassa reservoirs located in the Zambezi river basin.

1.1 Objectives

The general objective is to assess the water use efficiency in the main economic activities in the Kariba, Kafue and Cahora Bassa reservoirs. The specific objectives are:

i. Analyze the trends of the main variables influencing water supply (flow in) and demand (flow out) in the Kafue, Kariba and Cahora Bassa reservoirs;

ii. Estimate the effects of climate change scenarios on hydropower profits;

iii. Estimate the effects of climate change on fish production profits; and

iv. Estimate water productivity in agricultural production.

2. Methodology

Water supply and demand trends

Trend analysis are used to answer the question of whether the values of a given variables are going up, down, or staying the same. Trends occur in two ways: (i) monotonic trend which represents a gradual change over time that is consistent in direction and (ii) step trend, which represents an abrupt shift at a specific point in time. In this study, trend analysis will help to answer the question whether the studied variables changes over time due to the changing climate conditions and or due to other variables (covariates). The trend analysis will be performed at reservoir level (Kafue, Kariba and Cahora Bassa) for variables representing water inflows to the reservoirs (water supply) and for variables representing water outflows from the reservoirs (water demand). The water supply variables to be analyzed are river inflows to the reservoirs, precipitation and volume of water in the reservoir over time and for water demand variables are evaporation, dam discharges and river flows to downstream. Various tests can be used to assess trend on a given variable. Donald et al. (2011) suggest the following tests presented in the table 1 below under the absence and presence of seasonality as well as without adjustment and with adjustment for covariate variables for analyzing trends.

Table1. Statistical tests for trend analysis

Seasonality status	**Type of test**	**Not adjusted for covariate**	**Adjusted for covariate**
No seasonality	Parametric	Linear regression of Y on t	Multiple linear regression of Y on X and t
	Mixed		Mann-Kendall on residual from regression of Y on t
	Nonparametric	Mann-Kendall	Mann-Kendall on residuals from LOWESS of Y on X
Seasonality	Parametric	Linear regression of Y on t and periodic functions	Multiple linear regression of Y on X, t, and periodic functions
	Mixed	Regression of deseasonalized Y on t	Seasonal Kendall from regression of Y on X
	Nonparametric	Seasonal Kendall on Y	Seasonal Kendall on residuals from LOWESS of Y on X

The tests listed above will be used to test trend depending on the occurrence or not of seasonality as well as the presence of other variables influencing the trend of the studied variables (covariates). It should be noted that nonparametric tests provide higher statistical power in case of no normality of the studied variable and are robust against outliers and large data gaps. Therefore, nonparametric tests will be preferred for the trend analysis in this study.

Effects of climate changes on hydropower profits

Several studies have analyzed the effects of climate change on hydropower efficiency. Examples include the studies by Kopytkovskiya, Gezab and McCrayb (2015), and Hirsch et al. (2014). In this study we apply the methodology used by Hirsch et al. (2014) to analyze the effects of climate change scenarios on profitability of the hydropower. Therefore, for estimating the effects of climate change scenarios on hydropower profits, the objective function to be optimized is expressed as follows:

$$\text{Max Profit} = \text{sum}\,(P_{tj} * G_{tj}) \quad (1)$$

with P_{tj} being the energy price at time t and hydropower j and G_{tj} the energy generated in time t at hydropower j. The hydropower j are equal to 1 (Kariba), 2 (Kafue) and 3 (Cahora Bassa).

The profit maximization problem described above is constrained by power generation function (equation 2), water balance equation of reservoir (equation 3), water storage bound (equation 4), discharges for hydropower production bounded by turbine capacity (equation 5) and minimum discharges bounded by residual flows (equation 6)

$$G_{tj} = \mu * \lambda * W_{tj} * H_{tj} \quad (2)$$

$$S_{tj} = S_{tj-1} + I_{tj-1} - (W_{tj-1} + R_{tj-1}) \quad (3)$$

$$S_{tjmin} \leq S_{tj} \leq S_{tjmax} \quad (4)$$

$$W_{tjmin} \leq W_{tj} \leq W_{tjmax} \quad (5)$$

$$R_{tj} \geq r_{tjmin} \quad (6)$$

In the equation 2, the amount of energy generated G_{tj} is a function of the water discharge through the turbine at time t and hydropower j (W_{tj}), the average head of reservoir at time t and hydropower j (H_{tj}) and and operational efficiency factor λ. The conversion factor μ converts the specific water flows W_{tj} into electricity G_{tj} (in MWh).

In the equation 3, the storage level at time t of the reservoir where is located hydropower j (S_{tj}) depends on the previous time(t-1) storage level (S_{t-1}), the natural inflows I_{t-1} between t and $t-1$, the amount of turbinated water at previous period $t-1$ (W_{tj-1}) and the residual flow at previous period $t-1$ (R_{tj-1}). The storage level at time t at hydropower j (S_{tj}) is bounded by minimal and maximal discharge (equation 4) and the discharge at hydropower (W_{tj}) is also bounded by its minimal and maximal discharges. Additionally, the water flow at time t in the reservoir where is located the hydropower j (R_{tj}) should be greater than the minimal flow stipulated by law (r_{tj}).

Different scenarios of sensitivity analysis of hydropower profits will be simulated under the different the water discharge through the turbine (W_{tj}), average head of reservoir (H_{tj}), storage level of the reservoirs (S_{tj}) and residual water flows (R_{tj}) using mathematical software.

Fish Production Model

Fish reproduction is a biological process which depends on the environmental conditions of the reservoir. Factors such as water temperature and PH as well as the quantity of water in the reservoir affects directly fish production and consequently the profits of the fish sector. The noticeable climate change in Zambezi river basin is changing the environmental condition in the reservoir and therefore fish production. However, the effects of these changes in the fish production are not yet known. Various authors like MRAG Ltd (1995); Haque et al.; (2003), Crentsil and Ukpong (2014) and Naohate (2013) have estimated the effects of climate related variables on fish production. Different from past studies we simulate the impact of possible climate change scenarios which will affect the level of the climate change variables (temperature, quantity of water at reservoir) on the profit resulting from fish production. First, we estimate the total cost related to the production of commercial fish[1] in Kafue, Kariba and Cahora Bassa reservoirs by adding variable and the fixed costs related to the production of commercial fish. Secondly, we will estimate the fish production function as follows:

$$log\ (Yj) = \boldsymbol{\alpha_{0j}}+\boldsymbol{\alpha_{nj}}log(\boldsymbol{Z})+\mu_n \qquad (7)$$

where Y_j is the quantity of fish produced in reservoir j and Z is vector of independente variables such as the price of the fish (*PF*), (i) the level of effort (LE) represented by the number of boasts involved in capturing fish, (ii) the volume of the water in the reservoir (VW), (iii) precipitation (PT), (iv) water temperature (*WT*), (v) dummy variables indicating different climate change scenarios such as drought and floods.

, μ_n is the error term following normal distribution with zero mean and constant variance and $\boldsymbol{\alpha_{0j}}$ and as $\boldsymbol{\alpha_{nj}}$ are the vectors of the estimated parameters.

In order to examine the efficiency of climate related variables we will compute the Marginal Value Products (MVPs) for the climate related variables from the results of the models described above as follows:

[1] We will concentrate on the most commercialized fish in the three reservoirs.

$$MVP= A_i(Y/X)*P_y= K*P_i \quad (8)$$

where MVP is the marginal value products of the i^{th} input, X_i, A is the output elasticity of the i^{th} input, Y is the average (mean) of the response variable in the production function, X is the average (mean) of the i^{th} input P_y is the average price of the produced good and or service Y, P_i is the average price of the i^{th} input and K is the allocative efficiency parameters of the i^{th} input. The input is over used if $K < 1$, under-utilized if $K > 1$, and the input is efficiently used if $K=1$.

Thirdly, we compose the profit function based on the estimated production function and the estimated costs and we will conduct sensitivity analysis of different climate change variables on fish production profits. This procedure will be helpful for identifying the critical climate change scenarios which may harm fish production profits at Zambezi river basin.

Water Productivity in Agricultural Production

Agriculture is one of the major economic activities in SSA. However, in SSA, agriculture is the largest user of water resources accounting for about 70% of the total water withdrawal. As water is becoming increasingly scarce resources, efficient use of this resource is becoming increasingly important. Water availability within the Zambezi river basin varies widely and therefore the value attributed to water by various agricultural producers also varies across the basin. This variation might influence the productivity of water in agricultural sector across the basin. Among the produced crops, sugarcane is one of the important crops which, is produced under irrigation. Sugarcane is both produced at upper and lower streams of the Zambezi river basin and especially in Zambia and Mozambique. Therefore, efficient use of water in agriculture sector in the basin can significantly improve with an improvement of water productivity for sugarcane production.

It is important to note that knowledge about water productivity is relevant to economists and engineers who are interested in efficient management of water resources. Especially, it helps to identify disproportionate water use or water limited yield gaps and thereby support improvements in agricultural water management.

The physical water productivity for a given crop (kg/m^3) is estimated as the ratio between the crop yield and the estimated volume of consumptive water used for crop production. Therefore, in this study the physical productivity of water will be estimated by using following equation:

$$WP=Y/WR \quad (9)$$

Where *WP* is water productivity measured in kg/m^3, Y is the average crop yield in kg, and *WR* is the total volume of water used for crop production. The sugarcane yield will be obtained from secondary data and mainly from the Ministry of Agriculture of the two countries. The sugarcane production water requirements will be estimated using the FAO model Crop Wat. According to FAO (2012), the FAO model Crop Wat (CROPWAT) has different modules to calculate different parameters such as reference evapotranspiration, crop-water requirements and irrigation water requirements. It uses climate and crop data and in order to allow the calculation of parameters from different countries, the CROPWAT software climatic database has been included in the CROPWAT software. The details of the CROPWAT model are presented in FAO (2012).

3. Data

The data to be used to perform the analysis described above will be from hydropower management agencies, the ministry of water affairs, ministry of agriculture, ministry of trade and industry, ministry of finance, and climatic stations of the countries where the hydropower is located. The availability of data is not yet known as the different sources were not yet approached for asking for data. There is a possibility of not having some type of data and under these circumstances; the available related data will be used as proxy for variables with missing data.

4. Work Plan

Table 1 below presents the schedule of the work plan.

Table 1. Schedule of the work plan

Description	**2017**			**2018**											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	
Inception report															
Literature review															
Data collection															
Data analysis and reporting															
Submission of draft report															
Revision of draft report															
Submission/publication of final report															

5. References

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