Macro-economy and river system modeling: A co-evolutionary framework applied to the Eastern Nile River Basin

Mohammed Basheer [1], Victor Nechifor [2], Alvaro Calzadilla [3], Julien Harou [1,4]

[1] Department of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, UK.

[2] Joint Research Centre, European Commission.

[3] Institute for Sustainable Resources, University College London, London, UK.

[4] Department of Civil, Environmental and Geomatic Engineering, University College London, London, UK.

Abstract

This study introduces a generic co-evolutionary macro-economy and river system modeling framework that integrates a monthly river system simulation model and an annual Computable General Equilibrium (CGE) model. This integrated modeling framework is based on open-source modeling tools. The simulation framework is demonstrated on the Eastern Nile Basin to examine the benefits of a cooperative operation approach for the Grand Ethiopian Renaissance Dam (GERD). The performance of the cooperative approach is compared to a GERD operation proposal discussed by Ethiopia, Sudan, and Egypt in early 2020 but not accepted by all parties. The two GERD operation approaches are examined across stochastic hydrologic sequences to test robustness to inter-annual variability.

Keywords: Computable general equilibrium; river system; large dams; Pywr; Pynsim; IFPRI standard CGE model

1. Introduction

Water and electricity are necessary inputs to many production activities and, thus, the economic development and well-being of societies. The scarcity and/or variability of freshwater and energy affect economic growth (Acaravci & Ozturk, 2010; Barbier, 2004; Brown & Upmanu, 2006; Kebede et al., 2010; Mozumder & Marathe, 2007; Soytas & Sari, 2003). Efficient use of the limited water and energy resources to achieve sustainable economic development requires understanding and quantifying river system-economy interactions.

Hydro-economic models are one analytical framework for quantifying the impact of changes in the infrastructure and operating rules of river systems on selected sectors of the economy (e.g., irrigated agriculture, energy production) (Brouwer & Hofkes, 2008; Harou et al., 2009). This class of models uses the economic value of water to drive or evaluate water allocation within spatial biophysical systems. Most hydro-economic models described by Harou et al. (2009) account for the spatial and temporal variability of the economic value of water but use a partial equilibrium economic modeling approach which does not include the effects of changes in secondary markets or general equilibrium effects. Brouwer & Hofkes (2008) describe several efforts to link biophysical (e.g., hydrological) simulation models to aggregated economy-wide models. Within this class of models, Computable General Equilibrium (CGE) models have been used with river system models to quantify the economy-wide impacts of changes in water or energy systems.

Several studies since then have used CGE models to quantify the economy-wide impacts of operating river system infrastructure (Kahsay et al., 2015, 2019; Robinson et al., 2012; Robinson & Gueneau, 2013; Strzepek et al., 2008; Wittwer, 2009). We identify two approaches in the literature for coupling CGE models with river system models in the context of multi-year storage dams: (1) unidirectional (2) bidirectional. In a unidirectional coupling scheme, CGE models are driven by exogenous resource availability shocks that are predetermined using river system models. In a bidirectional coupling scheme, the CGE model computes the water and/or electricity needs of the economy based on exogenous economic parameters and behavioral equations of agents. The river system model then determines resource availability and passes this information back to the CGE model, which subsequently determines the economy-wide impacts based on resource availability.

2. Study contribution

This study introduces a bidirectional co-evolutionary macro-economy and river system modeling framework that integrates a monthly river system simulation model with a Computable General Equilibrium (CGE) model. This study is the first to consider water (irrigation and municipal water supplies) and electricity (hydropower and a spatially lumped representation of non-hydropower) linkages between a CGE model and a river system model using an iterative bidirectional approach. In reality, economic growth affects water and electricity demands, and the abundance or scarcity of water and electricity have a feedback effect on economic growth (Hertel & Liu, 2019). At each annual time step, the two models perform iterative bidirectional communication. The CGE model quantifies changes to annual water and electricity demands and non-hydropower electricity generation capacity, and the river system model attempts to meet the water and electricity demands subject to the spatial and temporal availability of river flow, infrastructure capacities (i.e., reservoir storage, non-hydropower, and hydropower capacities), and infrastructure operating rules. The economy and river system models are developed and connected using open-source modeling frameworks (see Figure 1). These include Pywr (generic Python library for simulating resource system networks; Tomlinson et al., (2020)), Pynsim (Python Network Simulation framework; Knox et al., (2018)), and the IFPRI (International Food Policy Research Institute) standard CGE model (Lofgren et al., 2002).

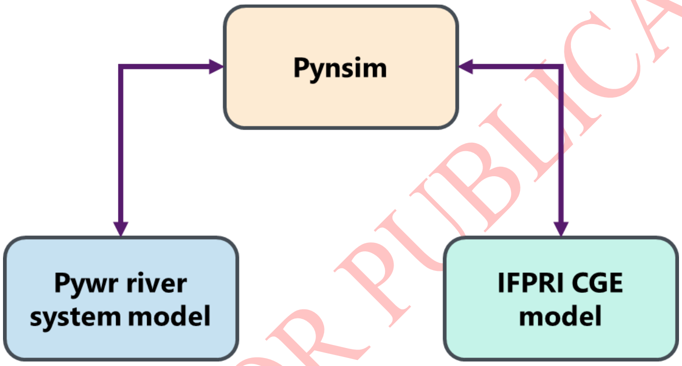

Figure 1 Flowchart of the open-source simulation frameworks used in developing the co-evolutionary macro-economy and river system modeling framework.

3. Application to the Eastern Nile Basin

The Eastern Nile Basin is one of the most continuous and hydro-politically complex river basins in the world. The basin area extends over five countries: Ethiopia, Sudan, Egypt, South Sudan, and Eritrea. On average, around 86% of the Nile water originates from Ethiopia. Historically, Egypt and Sudan have been the most significant consumers of the Nile water. In recent years, Ethiopia started utilizing the Nile water for hydropower production. The construction of the Grand Ethiopian Renaissance Dam (GERD) on the Nile in Ethiopia near the Ethiopian-Sudanese border caused significant political tension between Ethiopia, Sudan, and Egypt. Once completed, the GERD will become the largest hydropower plant in Africa and among the largest globally. We demonstrate the co-evolutionary macro-economy and river system modeling framework on the Eastern Nile River System and the GERD. We examine the benefits of a cooperative management approach for the GERD, whereby the GERD helps meet irrigation water demands in Egypt during droughts and increases water storage during periods of high flows. The performance of the cooperative management approach is compared with a recent GERD operation proposal negotiated by Ethiopia, Sudan, and Egypt in Washington D.C. (From November 2019 to February 2020) but has not been accepted by Ethiopia. In the Washington proposal, drought impacts on Egypt are mitigated through three main mechanisms (Edrees, 2020): (a) a minimum annual GERD water release, (b) a four-year minimum average annual GERD water release, and (c) a five-year minimum average annual GERD water release. The “cooperative management” and the “Washington proposal” GERD operation approaches are simulated over a 30 years simulation period (2020-2049) and cross 102 river flow sequences (‘traces’) developed using the index-sequential method (Ouarda et al., 1997). Figure 2 shows the flow of information between the Eastern Nile river system model and the computable general equilibrium models of Ethiopia, Sudan, and Egypt used in this study.

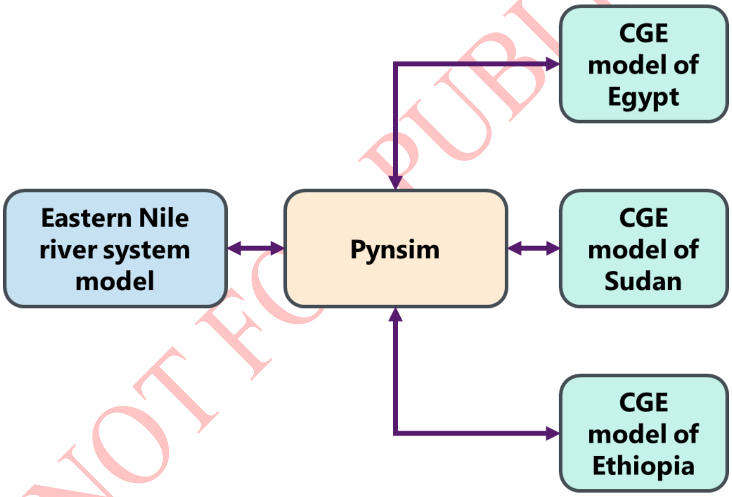

Figure 2 Flow chart of the iterative connections between the Eastern Nile river system model and the Computable General Equilibrium (CGE) models of Ethiopia, Sudan, and Egypt.

4. Computational performance of the modeling framework

For the cooperative management scenario, Figures 3a and 3b show the number of iterations and the convergence error, respectively. Figure 1a illustrates that the model required at least two iterations to converge at each annual time step. Egypt’s GDP was used to test model convergence based on a US$ 0.1 million error and a maximum of 50 iterations per annual time step. Results show that the number of iterations increases when curtailments to water and/or electricity supplies occur. This is because the demands for resources readjust when curtailments occur. The convergence error (Figure 3b) increases with the increase of water and/or electricity land supply shortfalls. The iterative communication between the river and the economy models results in increased computational accuracy within the specified maximum number of iterations. Figure 3a shows that the specified maximum number of iterations was reached only once without convergence. In that one case, the error was around US$ 1.4 million.

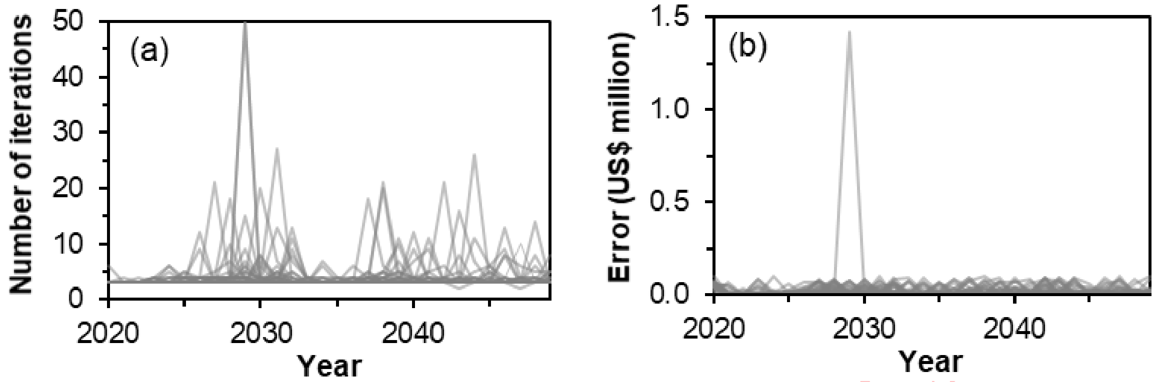

Figure 3 Computational performance in the cooperative management scenario based on Egypt's GDP as a convergence metric: (a) time series of the number of iterations; (d) time series of the convergence error. The multiple grey lines represent the 102 river flow traces.

5. Impacts of cooperative management on economic performance in the Nile Basin

Figure 4 depicts time series of the change in the Egyptian and Ethiopian GDP at market prices due to cooperative management of the GERD compared to the Washington Proposal. Figure 4a shows that Egypt's GDP decreases in the first 5-10 years of the simulation period. This occurs due to a decrease in hydropower production in this period as a result of a faster GERD initial filling in the cooperative management scenario compared to the Washington Proposal. Following that period, Egypt's GDP increase as a result of a decline in irrigation water shortages. Better irrigation water availability increases the production of all Egyptian sectors and increases investment. The increase in investment is due to an increase in households' and enterprises' savings.

Figure 4b shows the change in Ethiopia's GDP in the cooperative management scenario of the GERD compared to the Washington Proposal. The figure shows benefits to the Ethiopian economy from cooperative management of the GERD, with predominant short-term and long-term increases in GDP. The temporary declines in GDP in the first five years of the simulation period are due to speeding up in the initial filling of the GERD, resulting in lower releases through hydropower turbines and lower electricity generation.

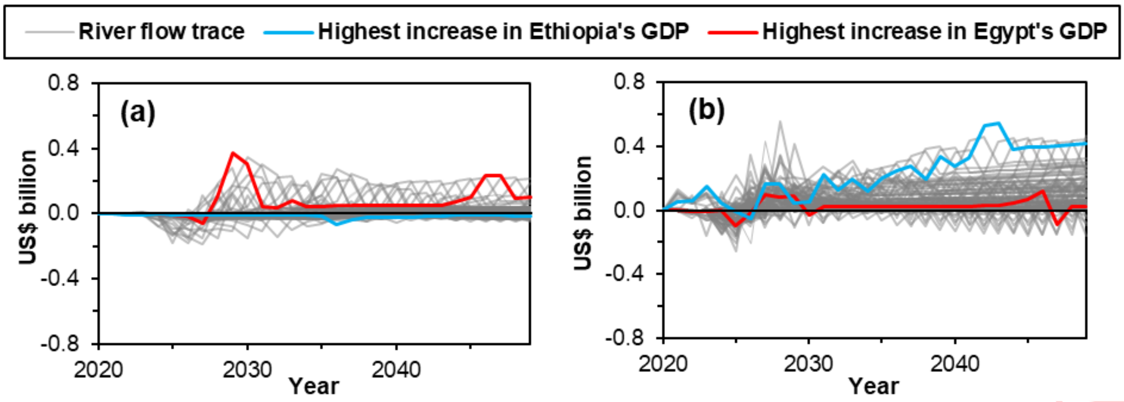

Figure 4 Time series of changes in GDP at market prices in the flexible collaboration scenario compared to the Washington Proposal: (a) Egypt; (b) Ethiopia.

6. Conclusions

River systems and the macro-economy are inherently interlinked. Modeling the interdependence of their integrated management could help better understand the impacts of changes to the river and/or economic systems. This study introduces a bidirectional co-evolutionary macro-economy and river system modeling framework. The framework integrates annual computable general equilibrium (CGE) models with a monthly river system model that incorporates a river basin with over-year water storage reservoirs and stochastic hydrology. Iterative bidirectional communication is performed to solve each annual time step. The river system and CGE models iterate to converge to similar water and electricity supplies in both models.

The simulation framework was applied to the Eastern Nile Basin to examine the benefits of a cooperative operation approach for the Grand Ethiopian Renaissance Dam (GERD). Results show that the Ethiopian and Egyptian economies would benefit from cooperative management of the GERD compared to the Washington Proposal, and Sudan's economy would be mostly indifferent. Implementing cooperative management in the Nile Basin requires trust and political commitment.

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