The Nile Water, Food and Energy Nexus Model

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ABSTRACT: The Water, Food and Energy (WFE) Nexus is a useful concept to address the interlinkages among these resources on which we depend to achieve socio-economic and environmental goals in a sustainable way. WFE are interconnected in different ways and an action in one sector would not only affect that but could have significant impacts on the other sectors. The Nile basin is a transboundary river which is currently challenged by rapid population and economic growth that sparked development plans aimed at meeting growing demands for WFE. Currently, water, food and energy are still managed separately and there is a little attention given to the interactions between the WFE and socio-economic drivers and the potential for a transboundary cooperation on WFE matters in the Nile basin. A System Dynamics Modelling (SDM) approach is proposed for this study as it: (a) provides a unique framework to address the interlinkages among subsystems in a complex dynamic system, and (b) has the ability to capture the dynamic feedback between system components. A water balance for the entire Nile basin is integrated with the food, energy, population and economic sectors in Egypt. The underlying structure of each submodel was presented. The calibration and the model simulations results were presented, and the model showed a satisfactory performance.

Keywords: Nile River, System Dynamics Modelling, Water, Food and Energy Nexus

„Neksus“ vode, energije i hrane u slivu reke Nil

APSTRAKT: Voda, energija i hrana su resursi od kojih zavisi u kojoj meri su društveno-ekonomski ciljevi i zaštita okoline u skladu sa principima održivog razvoja. „Neksus“ – *engl. water, food and energy (WFE) nexus* – je koncept koji proučava složene veze između ovih resursa. One se ogledaju u tome što mere preduzete u jednom od ova tri sektora imaju direktan uticaj na druga dva. U ovom radu se razmatra reka Nil koja prolazi kroz jedanaest zemalja, i u čijem slivu je u poslednjih nekoliko decenija došlo do znatnog porasta stanovništva i do ubrzanih ekonomskih aktivnosti. Zbog toga je neophodno da se planovi razvoja usklade sa rastućim potrebama. Međutim, upravljanje vodama i proizvodnja, distribucija i potrošnja energije i hrane u ovom slivu u praksi se razmatraju zasebno i nedovoljna pažnja se posvećuje međunarodnoj saradnji i proučavanju interakcija između ovih resursa i sa njima povezanim društveno-ekonomskim procesima. Modeliranje dinamike sistema – *engl. System Dynamics Modelling* – je pristup koji omogućava razmatranje veza između podsistema u okviru jednog složenog dinamičkog sistema, uz obuhvatanje povratnih sprega između različitih komponenti. Vodni bilans celog sliva reke Nil je u ovom radu integrisan sa informacijama o hrani, energiji, stanovništvu i ekonomskim sektorima u Egiptu i opisana je struktura svih elemenata sistema. Prikazani su rezultati kalibracije i simulacije, koji su zadovoljavajući.

Ključne reči: reka Nil, modeliranje dinamike sistema, neksus vode, energije i hrane

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1 Introduction

The Water, Food, Energy (WFE) Nexus approach is considered a useful concept to address the interrelated human activities and the natural resources e.g. river basins. The interlinkages among water, food and energy seem clear in many ways. From food production perspective, the water and energy are inputs, from an energy perspective, water and biomass (e.g. biofuels) are resources requirements. It is clear that the nexus resources are interdependent in many ways and the action in one sector would not only affect that sector but can have significant impacts on the other sectors. The WFE Nexus is challenging in transboundary rivers. Due to rapid population and economic growth in riparian countries, each riparian country continues to utilize its own natural resources to meet the growing demand for water, food, and energy. This might lead to tensions among countries that share the same resource. That makes a nexus approach is an appropriate approach for addressing the water management over a transboundary river as it can reveal the potential for a win-win situation and ease the conflict by mobilizing other resource potentials to meet the growing resource needs [1]. The Nile basin is a transboundary river, spreads across 11 countries (Tanzania, Uganda, Rwanda, Burundi, Congo (Kinshasa), Kenya, Ethiopia, Eretria, South Sudan, Sudan and Egypt), Figure 1. The river is one of the most complex rivers in the world because of its transboundary nature, i.e., its size, a variety of climates and topographies, and the high system evaporation losses [2]. The basin is confronted by a rapid population increase and economic growth in turn, a number of developments (e.g. Hydropower, irrigation projects, etc.) have been planned by the riparian countries to meet their growing demands for water, food and energy [3]. The nexus approach is relevant for Transboundary Rivers as it provides a policy framework for riparian countries to coordinate their plans, manage their measures in water, food and energy and reveal the tradeoffs and synergies from their actions [4].

Figure 1. The Nile basin.

Slika 1. Sliv reke Nil.

The dual interactions between sectors e.g. (water, and food), or (water and energy) were examined in various studies for example (Zhuang, Yilin [5], Kotir et al. [6], and Susnik et al., [7]). Extensive studies have been conducted to investigate the water resources management in the Nile basin e.g (Georgakakos [8]; Abdelhaleem and Helal [9]; Wheeler et al. [10]; Guariso and Whittington [11]; McCartney, et al. [12]; and Blackmore and Whittington [13]). The previous studies provided various frameworks to evaluate the tradeoff and synergies from new developments across the basin under different management scenarios, some of them could include the socio-economic drivers to the water system and provide an integrated framework to evaluate their impacts on the water system. However, these studies explicitly focusing on water and the WFE interdependency were not addressed in most of these studies, and most some of them are deterministic models. There are few studies considered the WFE nexus in the Nile basin recently. Tan et al. [14], studied the water, food and energy in the Blue Nile basin in the context of different operating policies for the Grand Renaissance Dam. They linked an optimization module to a System Dynamics model to investigate the different operating policies of GERD. However, the food production were not considered in their research. Al-Riffai et al. [15], employed a framework for the WFE nexus and its impacts on the economies of the Eastern Nile countries (Egypt, Ethiopia, and Sudan). Basheer et al. [15] studied the cooperation and the economic gains in the Blue Nile basin in the context of water, food and energy. Elgafy et al. [16] developed a system dynamics model for the water, food, and energy model (SD-WFEN) and applied it for Egypt and focused on the crop production and consumption. However, the causal feedbacks, the interactions among the WFE, and the socio-economic dynamics were not considered in most of these studies. To address the interactions among the WFE there is a need to address them equally and recognize their interdependency in an integrated analysis, [17, 18]. The current paper investigates the WFE interactions and socio-economic dynamics in the Nile basin and the policy implications and different management scenarios on the WEF in the Nile basin. For this purpose, a water balance model for the entire Nile basin was linked to the food, energy with the socio-economic sectors in Egypt.

2 Modelling framework

The interactions among socioeconomic and the WFE interlinkages are shown in Figure 2. A water balance model for the entire Nile basin is linked to the food production system and the energy sector in Egypt. The socio-economic drivers were added to the WFE Nexus to complete the framework and allow investigating the policy implications and the different management scenarios from a broader nexus perspective. System Dynamics Modelling (SDM) was chosen for this study because of its ability to; (a) combine the socio-economic dynamics, and WFE Nexus without any additional software packages, (b) capture the interdependency and the feedback processes among the WFE and the socio-economic sectors, (c) evaluate different policy and management options in the different sectors.

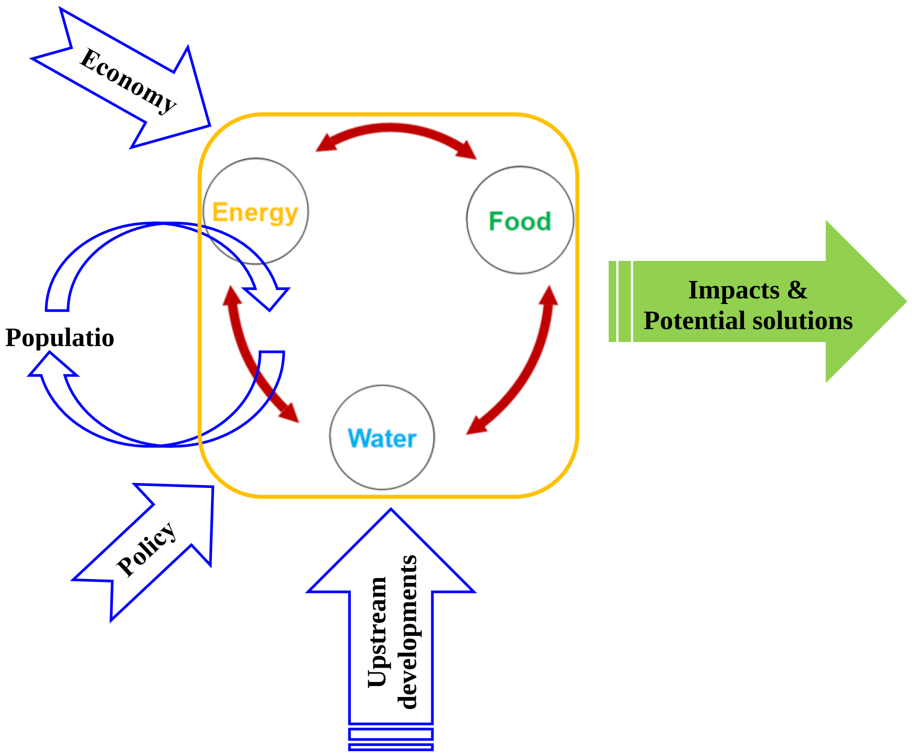

Figure 2. Water, Food, Energy Nexus modelling framework.

Slika 2. Modeliranje u okviru „neksusa“ vode, hrane i energije.

SDM is based on nonlinear dynamics theory and feedback control and has been widely applied to business and strategy [19] and environmental studies globally and regionally [20, 21]. It is a system-level modelling approach and can be applied to any dynamic system at various temporal and spatial scales [19]. These advantages favour the conventional modelling approaches and make SDM appropriate for modelling the interdependency among water, food and energy and the socio-economic dynamics. SDM starts with qualitative conceptual modelling, where the causal relationships and the feedback structure among key system variables are captured in the form of Causal Loop Diagrams (CLDs). Then, CLDs are quantified through Stock and Flow Diagrams (SFDs), where the system is represented by a network of connected stocks and flows. The CLDs composed of variables connected by arrows headed with a positive or negative sign, which reflects the causal relationship among the system variables (i.e positive sign means positive relationship while a negative sign means negative relationship). The combination of positive and negative causal relationships might form two types of feedback loops [22]: (a) reinforcing feedback loop, and (b) balancing feedback loop. A reinforcing feedback loop is characterized by the continuation of increase or decline in the system state, while a balancing loop tries to reduce the difference between the current state and the desired state of the system. System Dynamics (SD) components are: (a) Stocks, which represent anything that accumulates (e.g., reservoir), (b) Flows, which are activities that fill or deplete stocks (e.g., inflow and outflow), (c) Connectors, which link model elements and transfer information among model elements, and (d) Converters, which include arithmetic operations that can be performed on flows and logical functions that operate the system (e.g., operating rules for a reservoir). The CLDs are shown in Figure 3.

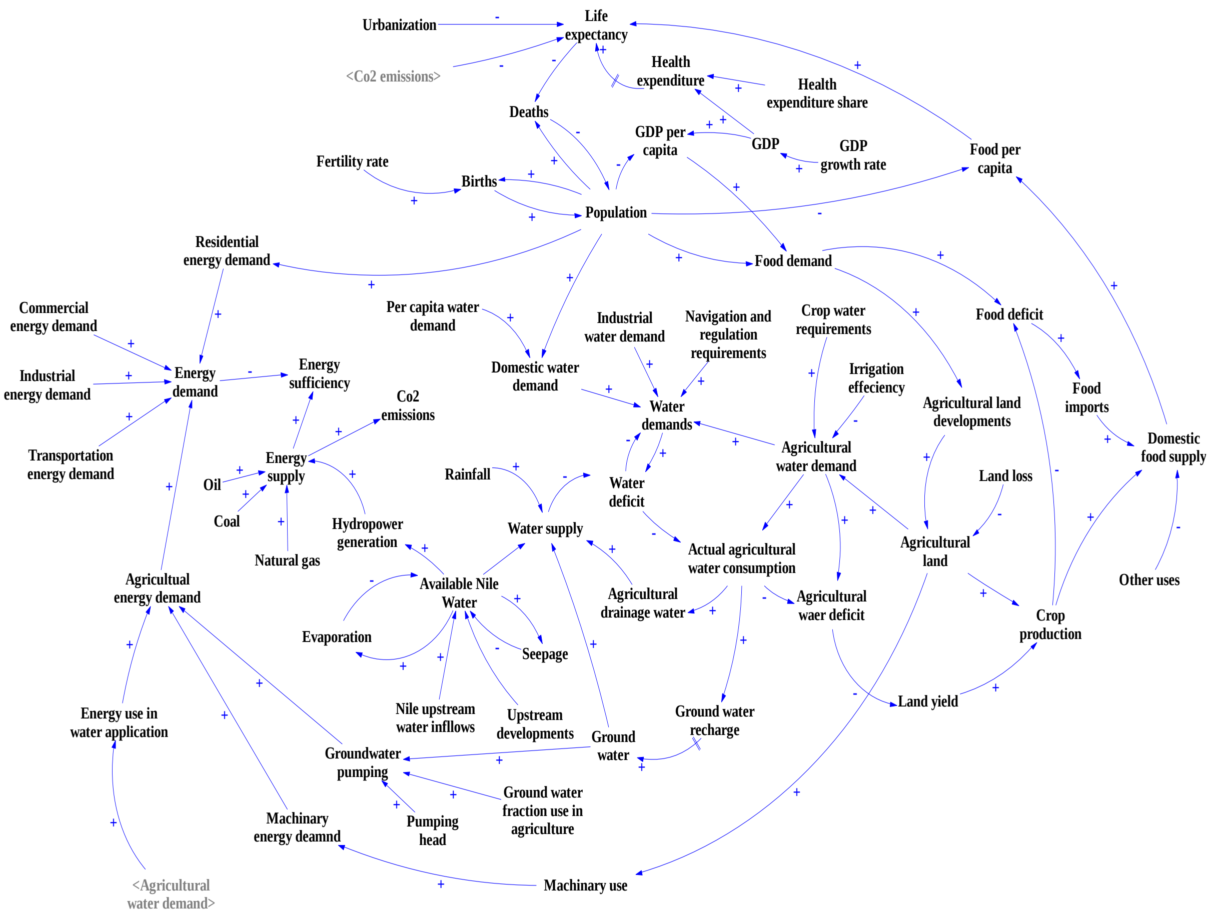

Figure 3. Causal loop diagram of the Water, Food and Energy interactions with the socio-economic drivers. A positive sign represents a positive causal relationship, and a negative sign represents a negative causal relationship. A link with a two-line bar in the middle represents a time delay.

Slika 3. Dijagram uzročno-posledičnih veza u interakcijama izmedju vode, hrane i energije i društveno-ekonomskih uticaja. Znak „+“ predstavlja pozitivnu vezu i znak „–“ je negativna veza. Veza sa znakom „═“ označava uticaj sa zakašnjenjem.

3 Model structure

The CLDs are quantified by SFDs for the Water, Food, Energy, Population and Economic sectors. The integrated model was implemented with Simile software [23]. Simile has an SD heart like other SDM software packages. It has a graphical user-friendly interface allowing to draw the model elements, their relationships easily and allows for breaking the system into sub-models, a feature was exploited in the current research. The underlying structure of the integrated model submodels are described below.

3.1 Water balance submodel

A water balance model for the entire Nile basin was developed to simulate the key hydrological features and different activities that affect the surface water availability (e.g., water withdrawals) and management of water infrastructures (e.g., dams and diversions). A description of the water balance is described here [24]. The water sub model showed a satisfactory performance and was able to simulate the dynamic behaviour of the Nile river flows.

3.2 Food submodel

The food sub-model represents the food production and consumption at the national level, Egypt. It is composed of three sub-models; (a) agriculture water demand sub model, (b) food production sub-model, and (c) food demand sub model. The interaction between the food production system and the water sector is captured through the agricultural sector in the model. The agricultural sector is represented by the agricultural land and the cropping patterns and used to estimate the agricultural water demands at the national level. The monthly crop water requirements (ETc) were calculated based on the FAO guidelines stated in the Irrigation and Drainage Paper No. 56, [25] as follows;

$$Et_c=K_c*E_o \quad (1)$$

Where;
Et_c: crop evapotranspiration (mm/month), K_c: crop factor
E_o: reference evapotranspiration (mm/month)

The food production considered here is the output from the cropland (domestic food production), fish and livestock can be omitted since it represents a small portion of the food consumption [20]. The domestic food production is estimated by multiplying the cropland by the crop yield, equation (2). In case of water shortage occurred, the reduction in crop yield due to water shortage can be calculated from equation (3), based on FAO guidelines for crop yield response to water shortage [26].

$$\text{Crop production}= A x Y_a \quad (2)$$

$$Y_a=Y_m x(1-K_y\ (1-(Et_a/ET_c)) \quad (3)$$

Where;
A: crop area (in feddan=1.038 Acres), Y_a: actual crop yield (ton/feddan)
Y_m: maximum possible yield (ton/feddan), ET_a: actual svapotranspiration
ET_c: maximum evapotranspiration, and K_y: yield response factor

The food demand sub-model represents the food demand from the population, and other food uses (e.g. animal feed and seeds). The average food consumption per capita depends on per capita Gross Domestic Product (GDP). Therefore, the Total Food Demand (TFD) can be estimated from the total population and average per capita food demand, equation (4). The food available for humans can be considered as a fraction of the total domestic food production i.e. after omitting the food waste, seeds, food exports and animal feed. If the local food available is not enough for meeting the food demands from populations the required food to be imported is called and can be estimated based on the food deficit, equation (5).

TFD= Percapita Food DemandxTotal Population (4)

$$\text{Food Imports} = \begin{cases} \text{(TFD- Human Food Available)} & \text{If (TFD- Human Food Available)} > 0 \\ 0 & \text{If (TFD- Human Food Available)} \leq 0 \end{cases} \quad (5)$$

3.3 The energy submodel

The energy submodel represents the energy sector in Egypt at the national level. It can be simply divided into two main parts; (a) energy supply and (b) energy demand. The energy supply represents the different energy supplies e.g. Natural gas, Crude oil, Hydropower, and Coal in the form of tone of oil equivalent (toe). While the energy demand represents the different sectoral energy demands e.g. Residential, Industrial, and Agricultural sectors in the form of (toe) as well. The model is under development and has not finished yet, the results from that sub-model or the underlying structure will not be presented here.

3.4 The population submodel

The population submodel represents the population dynamics for Egypt. The sub model is divided into fourteen age-specific groups; each age group represents a five-year span, except the elderly age group (65 and above). The population increased by the new births and they enter through the first age group (0-4), while the other age groups increased through ageing of the younger age groups (i.e maturation) equation (6). The delay in maturation from each age-specific group to the next age group is assumed as a first-order delay, by assuming the delay will be equal to the average number of years each person will stay in that group i.e. 5 years. On the other hand, the population is decreased by deaths and the ageing from younger age group to the next elder age group, equation (7).

$\text{Maturation}_{agegrouop}=\text{Population}_{agegrouop}\text{x}(1\text{-Mortality rate}_{agegrouop})/5$ (6)
$\text{Deaths}_{agegrouop}=\text{Population}_{agegrouop}\text{xMortality rate}_{agegrouop}$ (7)

3.5 The economic submodel

The sub model models the GDP for Egypt at an aggregated level. It uses a simple first order accumulation on GDP through a reinforced loop (growth rate in GDP). The per capita GDP is then estimated by dividing the total GDP by the total population.

$GDP_{t+1}=GDP_t\text{x}(1+r_{gdp})$ (8)
Where;
GDP_{t+1}: GDP at time (t+1)
GDP_t: GDP at time (t)
r_{gdp}: Annual GDP growth rate
GDP per capita=GDP/Total population (9)

4 Data sources

The available basin-wide hydrologic inputs, current and historical irrigation abstractions and diversions for the period (1950-2014), reservoir operating rules were available from MIKE HYDRO BASIN model that is linked to the Nile Basin Decision Support System (NB-DSS) [27]. Different water uses (e.g. Agricultural, domestic, industrial, open water evaporation, etc.), and water resources (e.g. groundwater, agricultural drainage reuse, rainfall data) in Egypt were obtained from Annual Bulletin of

Irrigation and Water Resources Statistics, Central Agency for Public Mobilization and Statistics (CAPMAS) [28] and the available data from literature [29-34]. Data for agricultural land, crops yield, and cropping patterns were available from Annual Bulletin of Statistical Crop Area and Plant Production, CAPMAS, Egypt [35] and FAOSTAT Database, FAO [36]. Food domestic production, food exports, food imports and different food uses (e.g. human consumption, seeds, loses, etc.) were available from Food Balance Sheets, FAOSTAT, FAO [36]. Different energy sources and consumptions were available from Energy balance from the International Energy Agency (IEA), [37]. Demographic data were obtained from the Population Division, Department of Economic and Social Affairs, United Nations (UN) [38]. Economic data (e.g. GDP, GDP growth rates) were obtained from the World Bank Open Data, The World Bank [39].

5 Model calibration and simulation results

The above-described submodels are interconnected and communicate with each other via links. The model defines a set of differential equations that have to be solved by numerical integration methods available in Simile. The model runs at a monthly time step from (1980-2014), based on the available data for all sectors. The software allows for visualization of the simulation results using tables and graphs. The model simulation results were graphically compared to the historical data records as shown in Figures (4-7). It is shown that the model simulation results follows the historical data trend, and there is a clear agreement between the simulated and observed data. The water balance submodel was calibrated at the key hydrological sites across the basin and the model showed a satisfactory performance based on guidelines provided by Moriasi et al [40]. The performance of other submodels was evaluated with the following statistical measures; Root Mean Square Percent Error (RMSE), Theil Inequality Coefficient test (TIC), and Theil Statistics test that measures the sources of error in terms of bias (UM), variance (US), and covariance (UC) between simulated and historical data [19]. The statistical tests results are shown in Table 1. The statistical tests showed that the RMSE is small and less than 10%, and the unsystematic errors are concentrated in US and UC, [19]. This shows the developed model has a clear agreement with the observed data and fits for the model purpose. To that point, the model showed a satisfactory performance for the developed sectors. The integrated model will be calibrated to evaluate the overall performance and its ability to capture interactions among WFE Nexus and socio-economic dynamics. Sensitivity and uncertainty analysis for the model predictions (e.g., model structure, model parameter values) will be conducted to assess the model robustness and its validity for its purpose.

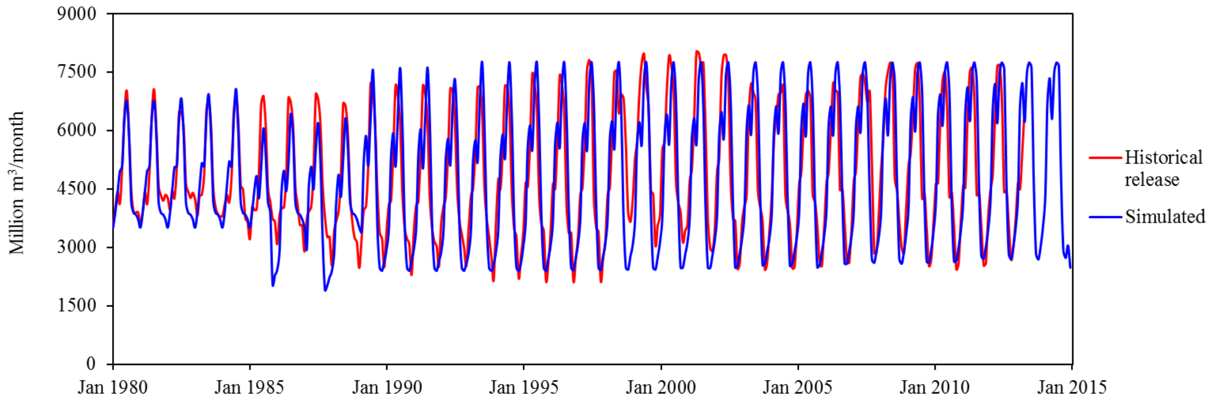

Figure 4. Model simulation results vs historical downstream release from High Aswan Dam.

Slika 4. Poređenje rezultata simulacije i izmerenih proticaja nizvodno of Nove asuanske brane.

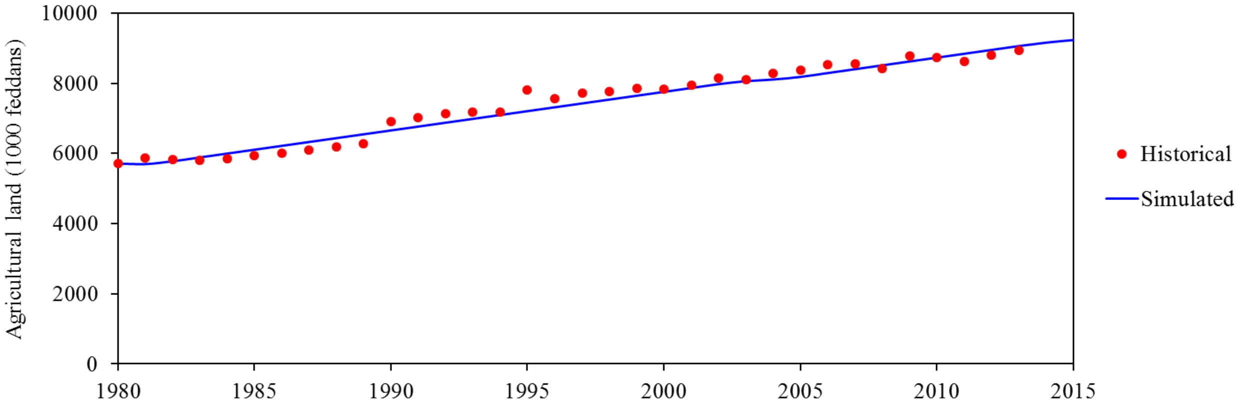

Figure 5. Model simulation results vs historical records of agricultural land.

Slika 5. Poređenje registrovanih poljoprivrednih površina sa rezultatima simulacije.

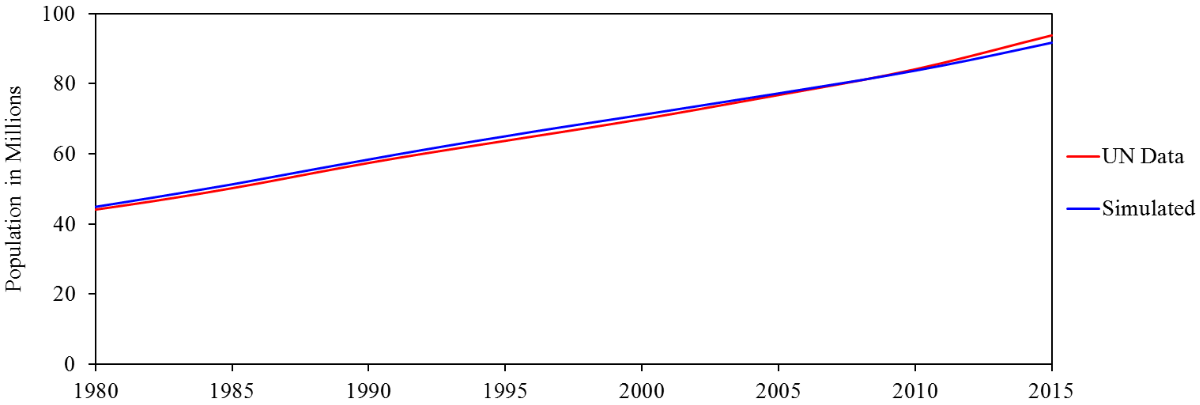

Figure 6. Model simulation results vs UN Population data.

Slika 6. Poređenje ukupnog stanovništva prema podacima Ujedinjenih nacija i na osnovu rezultata simulacije.

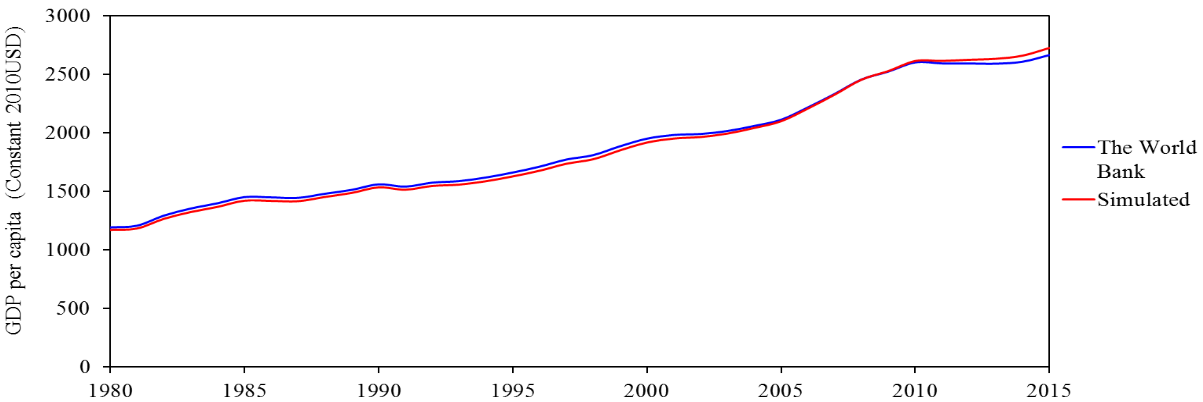

Figure 7. GDP per capita simulated vs The World Bank data.

Slika 7. Poređenje bruto nacionalnog dohotka po stanovniku prema podacima Svetske banke i na osnovu rezultata simulacije.

Table 1. Statistical parameters of the model tests.

Tabela 1. Statistički parametri testiranja modela.

Variable	RMSE (%)	TIC	Theil Inequality Statistics		
			U^M	U^S	U^C
Population	0.017	0.008	0.28	0.42	0.30
Agricultural land	0.029	0.014	0.09	0.04	0.87
GDP per capita	0.017	0.008	0.25	0.50	0.25
Note: $0 \leq TIC \leq 1.0$ (0 perfect prediction, 1.0 worst prediction) $U^M+U^S+U^C=1.0$					

6 Conclusions

The current paper described a methodology for integrating the WFE interactions with the socio-economic dynamics in the Nile basin by focusing on the last downstream country in the basin, Egypt. A System Dynamics Model was built for investigating the policy implications on the WFE in the Nile basin. The developed model showed a satisfactory performance and reflected the SDM ability to capture the interactions and the feedbacks among the WFE and the socio-economic dynamics in Egypt. The completion of the integrated model will be followed by formal calibration, sensitivity and uncertainty analysis to ensure the model robustness, validity and fits for its purpose. The model will be used to explore different policy options and management scenarios for the WFE and socio-economics in the Nile basin. For example population growth, changing crop patterns, improving the irrigation efficiency, upstream water developments, e.g., new reservoirs and agricultural projects.

Acknowledgements

The first author would like to express his gratitude to the Ministry of Higher Education (MoHE), Egypt and College of Engineering, Mathematics and Physical Sciences, University of Exeter, UK for the financial support for this research (PhD Scholarship) and to the University of Exeter for providing the tools and facilities to execute this work, and also to DHI Group for providing free licenses of MIKE HYDRO BASIN and MIKE HYDRO RIVER.

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