Nexus Assessment for Water, Food, and Energy System and the Implications on Human Development

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Abstract

Water, food, and energy are basic needs crucial to human survival but also pervade many aspects of human development. Systemically, they are vastly interdependent. In order to gain insight into the dynamics behaviour of water, food, and energy systems and their interactions to human development, a system dynamics model has been constructed. The model is structurally designed to generate behaviour of the system of interest at a national level and on an annual basis. The model is generic but purposely designed for Indonesia case, and hence it was subjected to behavioural test against national historical data of Indonesia. Test results show that the simulated behaviour of key elements of the model such as population size, income per capita, life expectancy at birth, water demands, crops demands and productions, and energy demands and productions, closely resemble behaviour of the actual data (i.e., pass the set criteria of the behavioural test). Model experiment with two different scenarios shows that our system model is sensitive to change in income per capita and energy demand. As part of future work, we will use the model to assess the implications of a range of policy scenarios on the water, food, and energy sector and on the human development index in Indonesia.

Keywords: water-food-energy nexus, human development index, system dynamics modelling

1. Introduction

Water, Food and Energy (WFE) are not just basic needs for human survival, but also pervade many aspects of human development. Several studies have been done to understand the interactions of WFE and human development. For example Pfister, Koehler, & Hellweg (2009) studied impact of freshwater deprivation on human health and found that water shortage for irrigation associate with malnutrition could causes three years lifetime lost; Jimenez, Molinero, & Perez-Foguet (2007) studied water poverty and human development index and found that the water poverty of a nation is not related to water scarcity but, rather, with the development level and per capita Gross National Product; the expansion of sanitation contributed to a 15-year increase in life expectancy in Great Britain in the four decades after 1880 as reported in (UNDP, 2006); Dias, Mattos, & P. Balestieri (2006) and Martínez & Ebenhack (2008) studied relationship of energy consumption and human development and found that there is a strong correlation between Human Development Index (HDI) and per capita energy consumption (i.e., steep rise of HDI occurs in energy-poor countries with HDI value 0.354 to 0.7, moderate rise of HDI occurs in transitioning countries with HDI value 0.7 to 0.9, and flat or no rise of HDI relative to energy consumption occurs in developed countries with HDI value greater than 0.9); Ray, Ghosh, Bardhan, & Bhattacharyya (2016) studied the impact of energy quality to human development in West Bengal, India and found that changing the use of traditional energy for cooking and lighting to modern and cleaner one, it can increases HDI to 16% up to 18%; Niu et al., (2013) and Ouedraogo (2013) studied the dynamic relationship between energy consumption and human development and found that there is long-run bidirectional causality exist between electricity consumption and per capita Gross Domestic Product (GDP), life expectancy at birth and the adult literacy rate.

These studies have provided some insights into the interaction of individual WFE sector and human development. However, they did not consider the interdependencies between each sector and the interplays with human development as an integrated system. Hence, we carried out a study to better understand the dynamics interaction of WFE sector as an integrated system and the linkages to human development.

2. Water-Food-Energy Nexus: An overview

2.1. Nexus Approach to Water-Food-Energy Security

Under the idea that we live in a world of extraordinary interdependence where everything is related to everything else (Senge, 2014; Tobler, 1970), the ‘nexus approach’ jargon emerges as efforts to solve multi-sectoral (or multi-systemic) problems in an integrated manner that differ from an independent or silo approach (Scott et al., 2015). Nexus approach presents a conceptual and analytical approach to address complex interactions and feedback between human and natural systems (FAO, 2014). One distinct feature of nexus approach compared to other integrated approaches such as Integrated Water Resources Management (IWRM) is it shifts a sector or resource-centric perspective to a multi-centric one (Bazilian et al., 2011; de Strasser et al., 2016).

Within the context of WFE systems (or sectors), the nexus approach is defined as an integrated approach to assessment, policy development, and implementation that focuses on water, food, and energy security simultaneously (Bizikova et al., 2014; Hoff, 2011). The elements of security of these resources may include their availability which involves production and distribution, their accessibility which involves affordability and allocation, their safety of being consumed, and their stability of supply relative to demand (Ericksen, 2008; Lele et al., 2013; Schmidhuber and Tubiello, 2007; Siwar and Ahmed, 2014; Winzer, 2012). WFE nexus approach allows investigation to understand the nature of the relationship among water, food, and energy systems and the consequences of change in one or more elements within the system. (Bizikova et al., 2013)

2.2. The Linkages of Water, Food, and Energy Systems

2.2.1. Food and Energy Linkages to Water Security

Food system influence water resources mostly through agriculture activities. Irrigation and drainage, consecutively, turns blue water into green water and vice versa (Savenije, 2000). Groundwater withdrawals is believed to cause rivers run dry quicker than surface water consumption (Savenije, 2000). Cover crops have been used to improve soil and water quality by increase evapotranspiration, enhance water infiltration into soil, slow runoff rates, and reduce soil erosion (Dabney, 1998; Dabney et al., 2007; Hoorman, 2009).

Energy availability is the limiting factor for water supply. It is estimated that energy needed to supply a cubic meter of water from surface water is 0.37 to 4 kWh, from groundwater is 0.48 kWh, from reused water is 1 to 6 kWh, from saline water is 2.6 to 8.5 kWh, and bottled water is 1000 to 4000 kWh (Olsson, 2013). Water pumping and distribution, drink water treatment, and wastewater treatment require energy.

2.2.2. Water and Energy Linkages to Food Security

Food production - either plant or animal production - depends on water supply and water quality. Plants and animals need water to grow. If water is limited, plant growth is limited with the same ratio (Gerbens-Leenes and Nonhebel, 2004). Animal feed production needs water for animal feeding and drinking during animal lifetime, and services such as clean the farmyard and wash the animal. Mekonnen & Hoekstra (2012) estimated global averages of water consumed in term of water footprint by several farm animal products, i.e., chicken meat product consumes 4,300 m^3 per ton, goat meat consumes 5,500 m^3 per ton, pig meat consumes 6,000 m^3 per ton, sheep meat consumes 10,400 m^3 per ton, and beef meet consumes 15,400 m^3 per ton. Total water footprint for global animal production during the period of 1996-2005 was 2,422 Gm^3 per year in which 87.2% came from rainwater (green water), 6.2% came from surface and ground water (blue water), and 6.6% came from reuse water (grey water) (Mekonnen and Hoekstra, 2012). It takes about 3 m^3 per day of water to produce enough food to satisfy a person's daily dietary or 7,700 km^3 per year for seven billion people on earth (Olsson, 2013). Water demand in food sector is estimated to increase by 45% in 2030 from present value (Olsson, 2013).

Energy is needed in almost all food production chain to final consumption to food waste disposal. Energy is needed for crop and livestock production and fishing, for food drying, cooling and storage, for food transport and distribution, for beverage processing, and for retailing, preparation and cooking. The food sector accounted for around 30% of the world's total primary energy consumption in 2011 (FAO, 2011). Energy consumed for cultivate, process, pack and bring food to European citizens' tables account for 26% of EU's final energy consumption in 2013 (JRC European Commission, 2015). Crop cultivation and animal rearing account for nearly one third of total energy use; industrial processing, logistics and packaging account for nearly half of the total energy use; and final disposal of food waste accounts for more than 5% of total energy use in EU food system (JRC European Commission, 2015).

2.2.3. Water and Food Linkages to Energy Security

Water is required in almost all energy production and electrical power generation. It makes water a limiting factor for energy generation unless technology improvements or alternative energy sources are considered. Almost all kinds of energy extraction require water. Table 1 summarize the water requirement for primary energy production. These linkages show that water security is also strongly tight to energy security.

Table 1 The water requirement for primary energy production (DOE, 2006)

Energy Process	Energy element	Water quantity
Extraction & production	Oil and gas exploration	Water for drilling, completion and fracturing
	Oil and gas production	Large volume of produced impaired water
	Coal and uranium mining	Larger quantities of water may be used
Refining & processing	Traditional oil & gas refining	Water needed to refine oil and gas
	Biofuels and ethanol	Water for growing and refining
	Synfuels and hydrogen	Water for synthesis or steam reforming
Transportation & storage	Energy pipelines	Water for hydrostatic testing
	Coal slurry pipelines	Water for slurry transport (not returning)
	Oil and gas storage caverns	Large quantities of water required for slurry mining caverns

Bioenergy such as biodiesel, bioethanol, and anaerobic digestion, present direct and indirect link between energy and food/food waste. Land as a means for growing food crops now can be used to grow energy crops.

3. Modelling Assessment for the Water-Food-Energy Nexus and Linkages to Human Development

3.1. System Dynamics Modelling

System Dynamics Modelling (SDM) - introduced by Jay Forrester (Forrester, 1989) - is a modelling technique capable to model feedback mechanisms that give rise to the nonlinear behaviours of most complex systems (Sterman, 2000, p. 12). There are two types of feedback mechanism or feedback loop in SDM, namely positive (or reinforcing) loop and negative (or balancing) loop. Positive loop reinforces while negative loop counteracts whatever is happening in the system.

Principally, SDM involves two stages process, first is model conceptualisation and second is model simulation. On the conceptualisation stage, a model structure of the system is identified and represented in the form of diagram called Causal Loop Diagram (CLD) to allow visual inspection of the feedback loops in the system (Madani and Mariño, 2009). CLD contains components of the system that are connected by arrows denoting the causal influence among the components. Each arrow is assigned a polarity, either positive (+) or negative (-) to indicated how two connected components are changes (i.e, positive polarity means two connected components changes proportionally while negative polarity means they changes in the opposite way) (Sterman, 2000, pp. 137–140). On the simulation stage, at first CLD is translated into a Stock Flow Diagram (SFD) in which elements or variables in the system are identified as stocks, flows, or auxiliaries, and the relationships among them in term of mathematical formula are obtained (Sterman, 2000, pp. 191–230). Once SFD is built, it can be simulated using computer software to generate system behaviour over time that can be presented in terms of graphs and numbers (Madani and Mariño, 2009).

Stock in SDM represents an entity in a system that is subject to change due to difference rate of its inflow and outflow. When the inflow rate is larger than outflow rate then entity will accumulate, conversely it will deplete.

SDM can be implement using various computer software such as STELLA, Vensim, Simile, and MATLAB/Simulink (Wikipedia, 2019). In this work, we used MATLAB/Simulink.

3.2. System of Interest and Boundaries

System that of interest to us are water, food, and energy resources. At each sectoral level, we were looking on the dynamic state of their availability, supply (e.g., production, export, and import), and demand. Yet, what we aimed to understand is the nexus (i.e., interrelationships) among them and their linkages to human development.

On the human development side, we interested on the key dimensions of human development which according to (HDRO Outreach, 2015), are a long and healthy life, being knowledgeable, and have a decent standard of living. These dimensions are quantified by four indicators, namely life expectancy at birth indicates state of a long and healthy life, expected and mean years of schooling indicate a state of being knowledgeable, and income per capita indicates a state of a decent living standard (HDRO, 2015). These indicators are further represented as a single composite index known as, Human Development Index (HDI). HDI have been used to compare level of human development among nations (Haq, 2003).

Furthermore, central to WEF system and human development is population size. It is the main driver of change to WEF system states (Hoff, 2011). Therefore, we also interested to see how population interacts with the WEF systems. The model output we expected is an integrated system model that was framed as depicted in Figure 1.

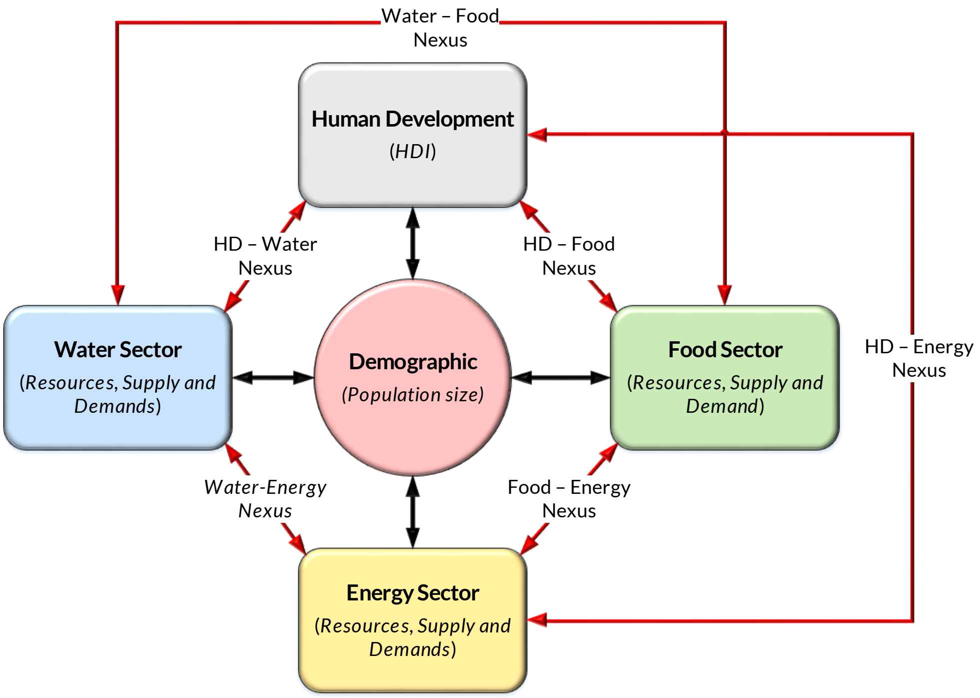


Figure 1 – Model Framework of WFE-HD Nexus

Figure 1 shows that our system model comprises five modules, namely water sector, energy sector, food sector, human development, and demographic. The system behaviours can be evaluated at various spatio-temporal scales however we chose to confine our locus to the behaviour of the system at the national level and over an annual period. Selected elements to be included in each module are treated either as endogenous or exogenous element. Endogenous element is element whose behaviour is influenced by other elements in the system. Exogenous element is element whose behaviour is not influenced by other elements in the system and may act as an input element. Table 1 lists key elements of each module in our model.

Table 1 Key elements of WEF-HD Nexus.

Module	Elements	Type of Element
Demographic	Total population	Endogenous
	Total Fertility Rate	Endogenous
	Mortality Rate	Endogenous
Human Development	Life expectancy	Endogenous
	Income per capita	Endogenous
	Mean year of schooling	Exogenous
	Expected year of schooling	Exogenous
Water	Rainfall	Exogenous
	Fresh water stocks	Endogenous
	Domestic water demand	Endogenous
	Industrial water demand	Endogenous
	Agricultural water demand	Endogenous
Energy	Energy stocks	Exogeneous
	Domestic energy demand	Endogenous
	Industrial energy demand	Endogenous
	Agricultural energy demand	Endogenous
Food	Irrigated land	Endogenous
	Crop production	Endogenous
	Crops demand	Endogenous
	Meat production	Endogenous
	Meat demand	Endogenous

3.3. Model Design

Purpose of developing this model are: (1) as a tool to evaluate the dynamics behaviours of WFE systems and their linkages to human development, and (2) as a tool to assess better policies formation on securing water, food, and energy and sustainably improving human development.

The model is generic, however, purposely develop to be implemented in Indonesia and hence subjected to calibration and validation against Indonesia national data. The following sub sections briefly describe model design for each individual module.

3.3.1. Demographic Module

Demographic module was developed to model the dynamics of population size. Total population is controlled by birth rate, death rate and net migration rate. Net migration is treated exogenously in our model. For birth rate, we considered income per capita as the only determinant of birth rate in our model. Income per capita is assumed equal to GDP per capita. Figure 2 shows a scatterplot of crude birth rate against GDP per capita for 217 countries from the year 1990 to 2015. Data were pooled from World Bank databank (World Bank, n.d.). It can be seen that the higher the income, the less the birth rate and vice versa. A second order polynomial curve of log GDP per capita fits the pair data quite well, and hence its mathematical function is used in our model. Death rate, on the other case is associated to life expectancy at birth. Hence, we use life expectancy at birth as determinant of death rate. Figure 3 shows a scatterplot of crude death rate against life expectancy at birth and the fitted curve. It shows that higher life expectancy at birth is translated to lower death rate and vice versa.

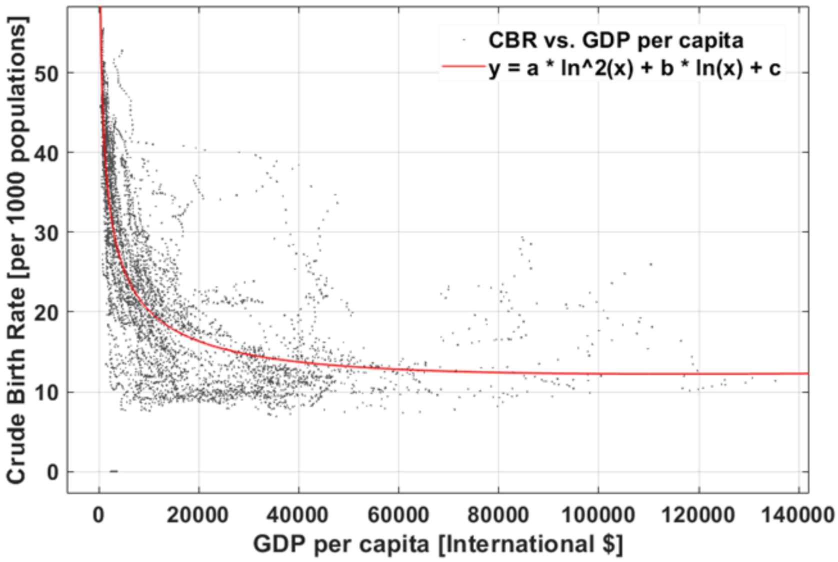


Figure 2 – CBR vs. GDP per capita

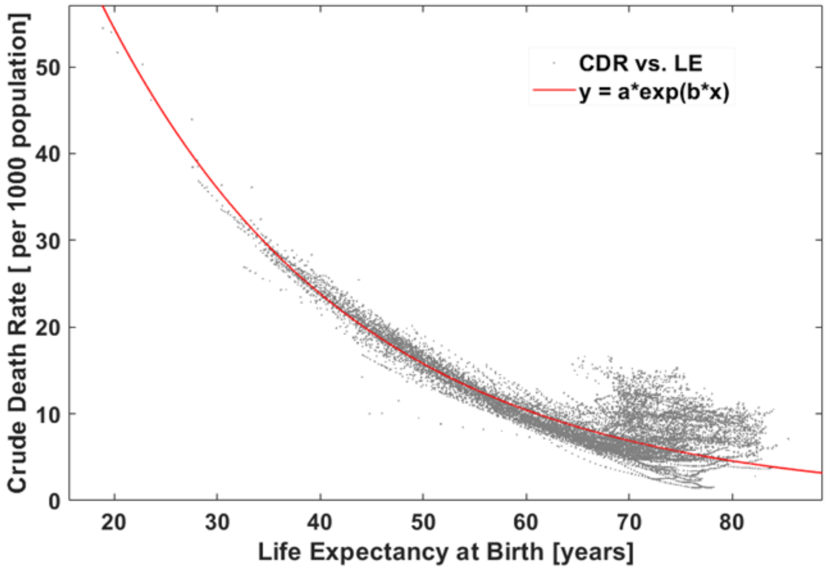


Figure 3 – CDR vs. Life Expectancy at Birth

The inputs to demographic module are income per capita and life expectancy. Both are generated in the human development module. Outputs from demographic module are total population. Figure 4 shows CLD for demographic module.

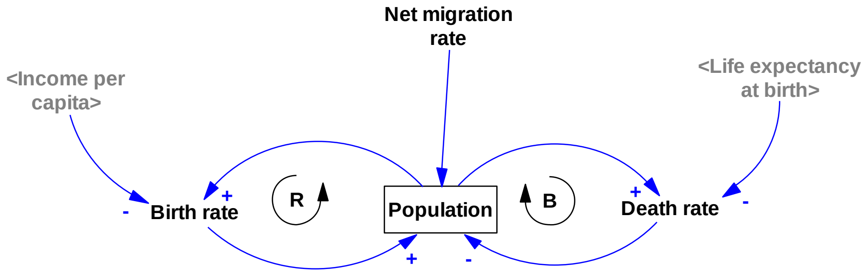


Figure 4 – CLD for demographic module

3.3.2. Human Development Module

The human development module was developed to model the dynamics of the four indicators of HDI. These are income per capita, life expectancy at birth, mean years of schooling and expected years of schooling. Life expectancy at birth and income per capita are generated endogenously, while mean and expected years of schooling are generated exogenously.
Income per capita is defined as Gross Domestic Product (GDP) per total population. GDP is modelled as a function of labour, stock capital, and energy production based on the LINEX production function after Kummel (Reiner Kiimmel et al., 1985). LINEX function can be expressed mathematically as follow:

$$GDP = q_o \cdot E_p \cdot e^{a_0 \cdot \left(2 - \frac{L+E_p}{K}\right) + a_0 \cdot c_t \cdot \left(\frac{L}{E_p} - 1\right)} \quad (1)$$

where E_p is energy production [GWh], L is labour [person], K is capital stocks [$], and q_o, a_o, c_t are LINEX parameters.

Life expectancy at birth is assumed to only affected by income per capita. Figure 5 shows a scatterplot of life expectancy at birth against GDP per capita and the fitted curve. It shows that the higher the income, the higher the life expectancy at birth.

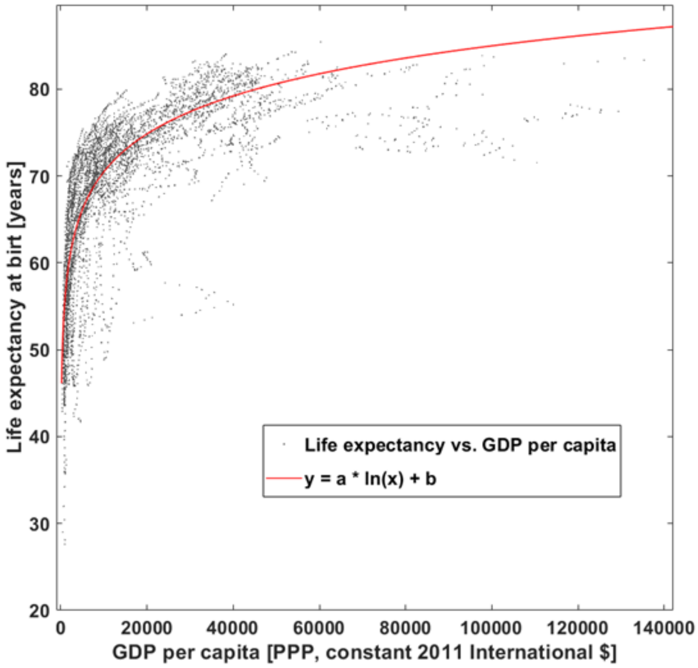


Figure 5 – Life expectancy at Birth vs. GDP per capita

The inputs to the human development module are population size, energy production, and capital stocks. The outputs from human development module are income per capita and life expectancy at birth. Figure 6 shows CLD for human development module.

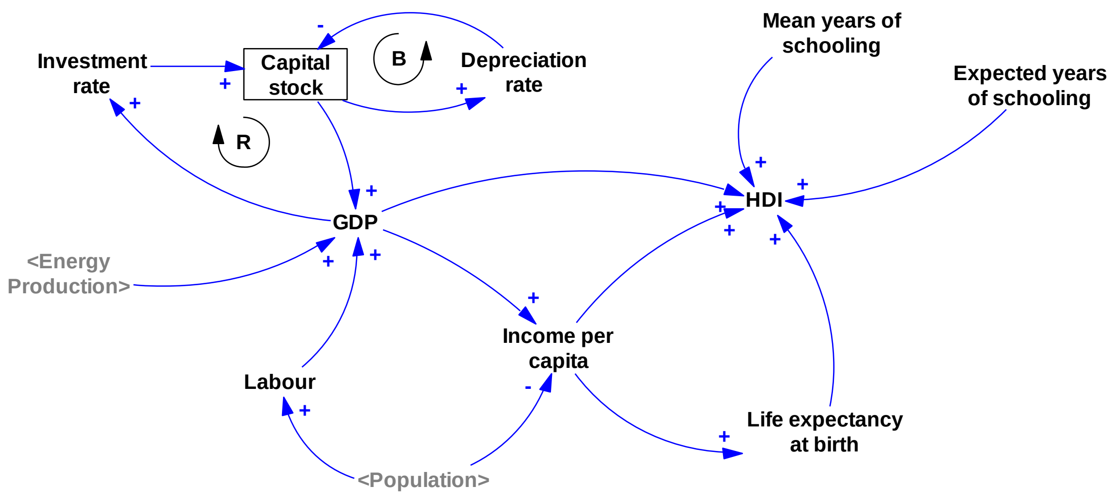


Figure 6 – CLD for demographic module

3.3.3. Water Sector Module

Water sector module was developed to model the dynamics of water resources availability and its demand. The model is developed based on water balance concept after Sokolov & Chapman (1974, p. 79). Mathematically, it can be expressed as follows:

$$P + Q_{sI} + Q_{uI} - ET - Q_{sO} - Q_{uO} - Q_\alpha + Q_\beta - \Delta S = 0 \quad (2)$$

where P is rainfall, Q_{sI} and Q_{uI} are surface and subsurface water inflow, ET is evapotranspiration, Q_{sO} and Q_{uO} are surface and subsurface water outflow, Q_α and Q_β are water withdrew from and return to the ground or river, and ΔS is water storage change.

At the annual scale, we assumed net change of storage is zero. We also assume no inflow water other than rainwater. Therefore, equation (2) becomes:

$$(P + Q_\beta) - (ET + Q + Q_\alpha) = 0 \quad (3)$$

Where, Q = $Q_{sO} + Q_{uO}$ is total runoff.

Rainfall (P) was treated exogenously. The total runoff (Q) was estimated using rainfall-runoff relationship proposed by Weert (1994) as follows:

$$Q = \begin{cases} 155 \cdot \left(\frac{P}{1000}\right)^{2.5} & for\ P < 1800\ mm/year \\ 0.94 \cdot P - 1018 & for\ P > 1800\ mm/year \end{cases} \quad (4)$$

On the demand side, total water demand was disaggregated into domestic, industrial, and agricultural water demand. Domestics and industrial water demand model were adopted from the WaterGAP model of Alcamo et al. (2003) as expressed mathematically in equation (5) and (6). Agricultural water demand was estimated using water footprint for selected crops and reference water consumption for selected livestock as expressed mathematically in equation (7). Total water demand is the sum of sectoral water demands (equation (8)).

$$DWD = \left(DSWI_{min} + DSWI_{max}\left(1 - e^{-\gamma_d \cdot IPC^2}\right)\right) \cdot (1 - \eta_d)^{t-t_0} \cdot Pop \quad (5)$$

$$IWD = \left(ISWI_{min} + \frac{1}{\gamma_i \cdot (IPC - IPC_{min})}\right) \cdot (1 - \eta_i)^{t-t_0} \cdot Elec_p \quad (6)$$

$$AWD = \sum_i (WFC_i \cdot C_i) + \sum_j \left(365 \cdot LWI_j \cdot LPop_j\right) \quad (7)$$

$$TWD = DWD + IWD + AWD \quad (8)$$

where *DWD*, *IWD, AWD,* and *TWD* are domestic, industrial, agricultural, and total water demand [m^3/year]; $DSWI_{min}$ and $DSWI_{max}$ are minimum and maximum domestic structural water intensity [m^3/person]; $ISWI_{min}$ is minimum industrial structural water intensity [m^3/MWh]; *Pop* is population [persons/year]; *IPC* and *IPCmin* are actual and minimum income per capita [$/person]; $Elec_p$ is electricity production [MWh]; WFC_i is water footprint for crop *i* [m^3/ton]; C_i is annual production of crop *i* [ton/year]; LWI_j is water intensity per unit of livestock *j* [m^3/day/head]; $LPop_j$ is total population of livestock *j* [head]; η_d and η_i are rate of improvement in the efficiency of domestic and industrial water use [dmsl]; γ_d and γ_i are curve parameters related to the effect of IPC on the domestics and industrial water intensity [dmsl].

Follows on the water balance expression in equation (2), total water withdrawal (Q_α) is assumed the same as total water demand (*TWD*) and Q_β or returned water was estimated as lumped fraction of sectoral water demands. Equation (9) and (10) express these assumptions mathematically.

$$Q_\alpha = TWD \quad (9)$$

$$Q_\beta = f_d \cdot DWD + f_i \cdot IWD + f_a \cdot AWD \qquad (10)$$

Where, f_d, f_i, and f_a are fraction of domestic, industrial, and agricultural water returned to the land and they are treated exogenously.

The inputs to the water sector module are population size, income per capita, energy production, crops production, and livestock. The outputs are total water stock, total water demand and sectoral water demand. Figure 7 shows CLD for water sector module.

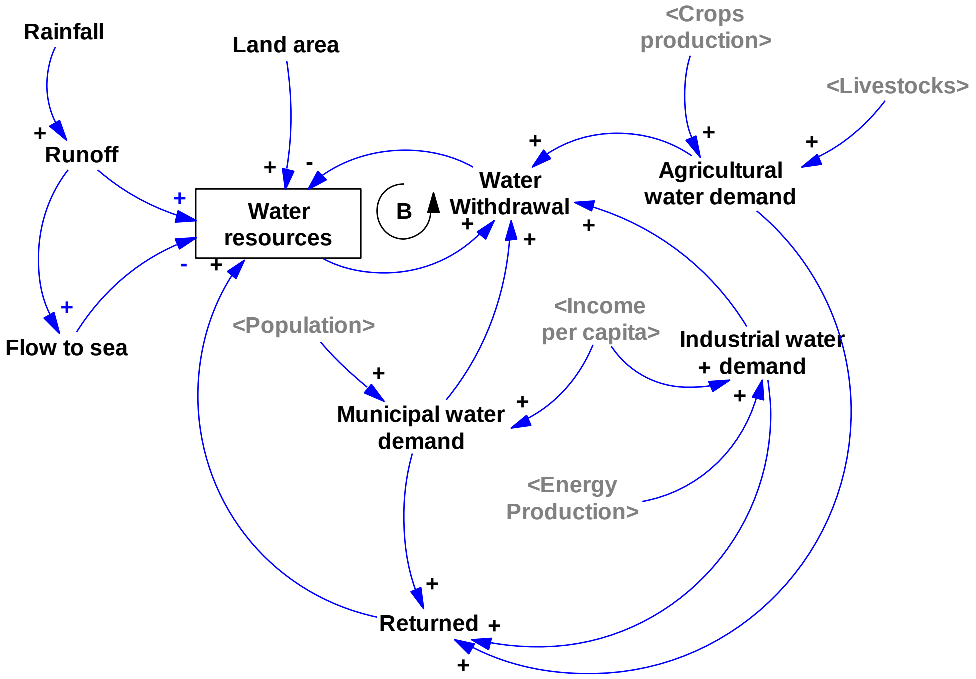


Figure 7 – CLD for water sector module

3.3.4. Energy Sector Module

Energy sector module was developed to model the dynamics of energy resources availability, energy supply, and demand. Energy resources is distinguished into renewables and non-renewables. Non-renewable energy in our model are oil, natural gas, and coal. Renewable energy include in our model are hydropower, geothermal, solar, wind, and biomass. Different with water, at the end use, some energy types require transformation, and hence we distinguished energy type into primary and secondary energy. Primary energy is type of energy that require transformation (e.g., crude oil) to be useful but also can be used directly, e.g., coal, gas, and biomass) without transformation. Secondary energy is type of energy that requires transformation from primary energy, e.g., oil fuels, LPG, and electricity.

On the supply side, energy supply is determined by production, import and export. However, import and export is modelled as difference of production and demand. If production is more than demand, then surplus energy is exported. Vice versa, if production is less than demand, then the shortage demand is obtained through import. Energy production is determined by production capacity and capacity factor but limited by resources availability. Energy demand is determined by the level of activity (i.e., number of customers) and the level of intensity per activity (i.e., how much energy demand per unit of costumer). Furthermore, we assumed level of intensity is influenced by economic level (i.e., income per capita). Costumers of energy in our model are segregated into households, industry, commercial, and transportation.

The inputs to the energy sector module are population size and income per capita. The outputs are energy reserves stock, primary and secondary energy production, and sectoral energy demand. Figure 8 shows CLD for energy sector module.

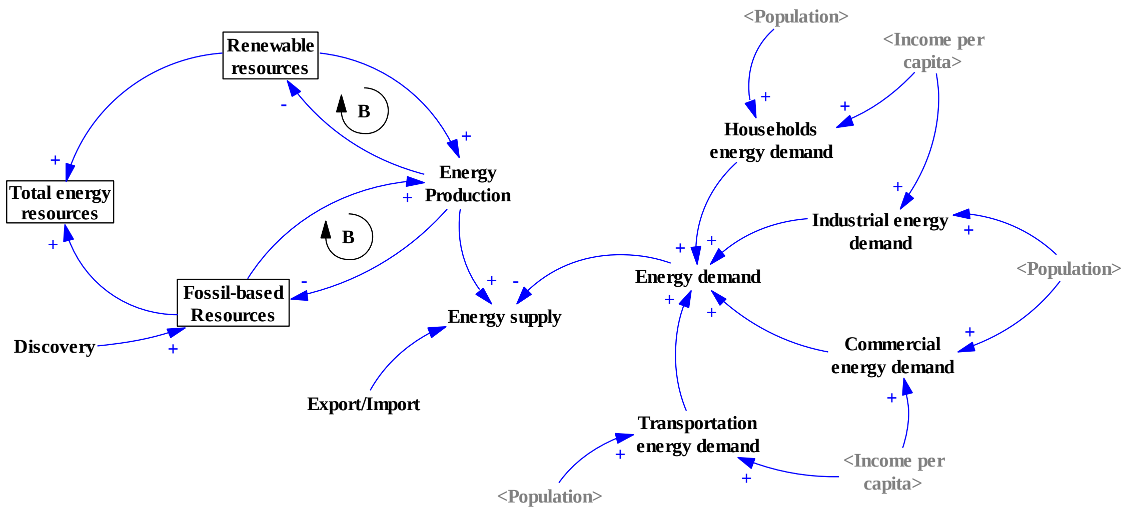


Figure 8 – CLD for energy sector module

3.3.5. Food Sector Module

Food sector was developed to model dynamics of food production and demand. Food type is distinguished into crops and meat. We only include certain type of crops and meats to be modelled. These are rice, maize, cassava, soybean, peanut, palm oil, cocoa, and coffee for crops; and beef, buffalo, lamb, goat, pork, and poultry for meats. On the demand side, crops and meats demand is influenced by income per capita and Consumer Price Index (CPI). However, CPI is treated exogenously. On the production side, crops production is determined by cropland area, cropping intensity, and productivity, while meat production is determined by multiplication of meat coefficient to the corresponding livestock population. Livestock population is treated exogenously.

The inputs to the food sector module are population size and income per capita. The outputs are crops and meet productions, crops and meet demand. Figure 9 shows CLD for food sector module.

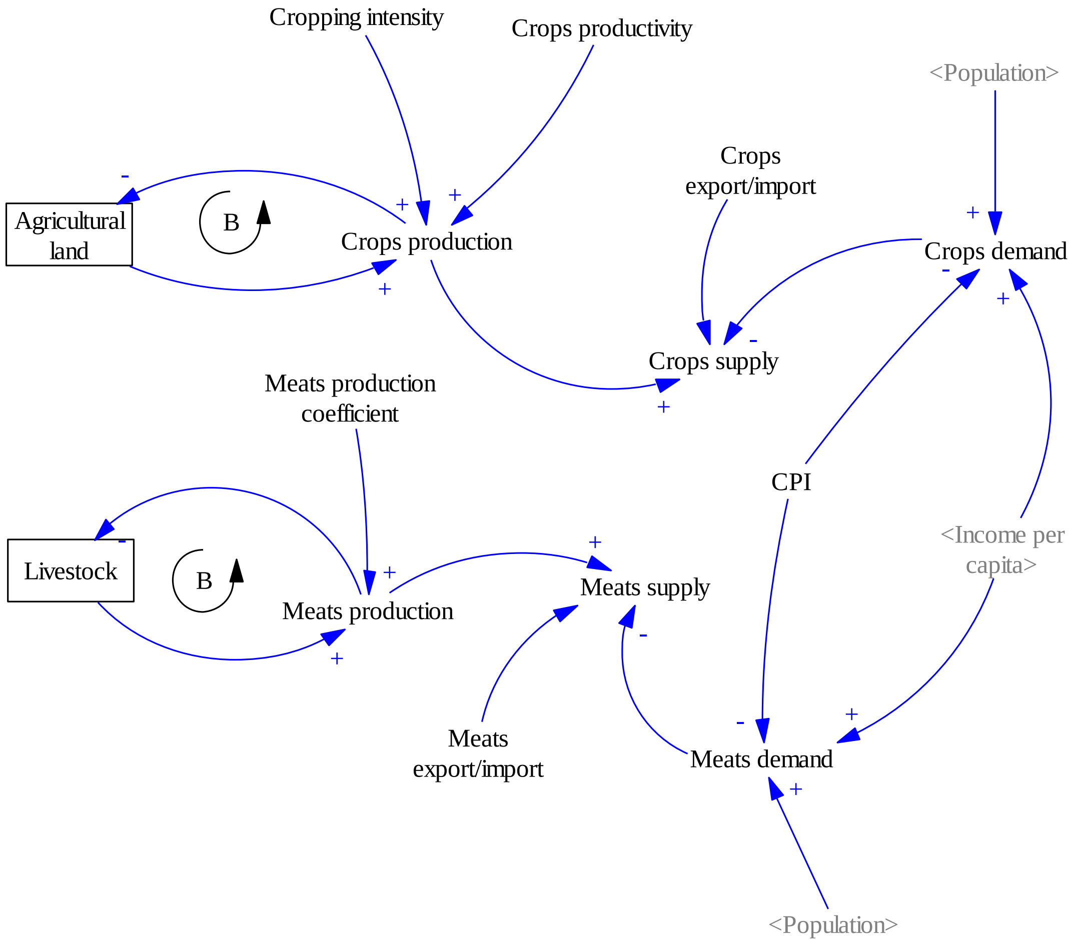


Figure 9 – CLD for food sector module

3.3.6. Integrated Module

Figure 10 shows CLD for the integrated model of each module at aggregated level. Several feedback loops which are denoting by R for reinforcing loop and B for balancing loop can be identified within each module or across modules which are useful for qualitatively determined the entire system behaviour. For example, within demographic module (i.e., denoting by pink colour for its components), population is reinforced by birth in R1-loop and balanced by death in B1- loop. It is also controlled by B2-loop (population → income per capita → birth rate → births → population) and R2-loop (population → income per capita → life expectancy at birth → death rate → deaths → population). At these parallel loops, population will be growing if R2-loop is dominant then B2-loop and vice versa. We can also inspect B3-loop (population → labour → GDP → income per capita → population) and R3-loop (population → energy demand → energy production → GDP → income per capita → population).

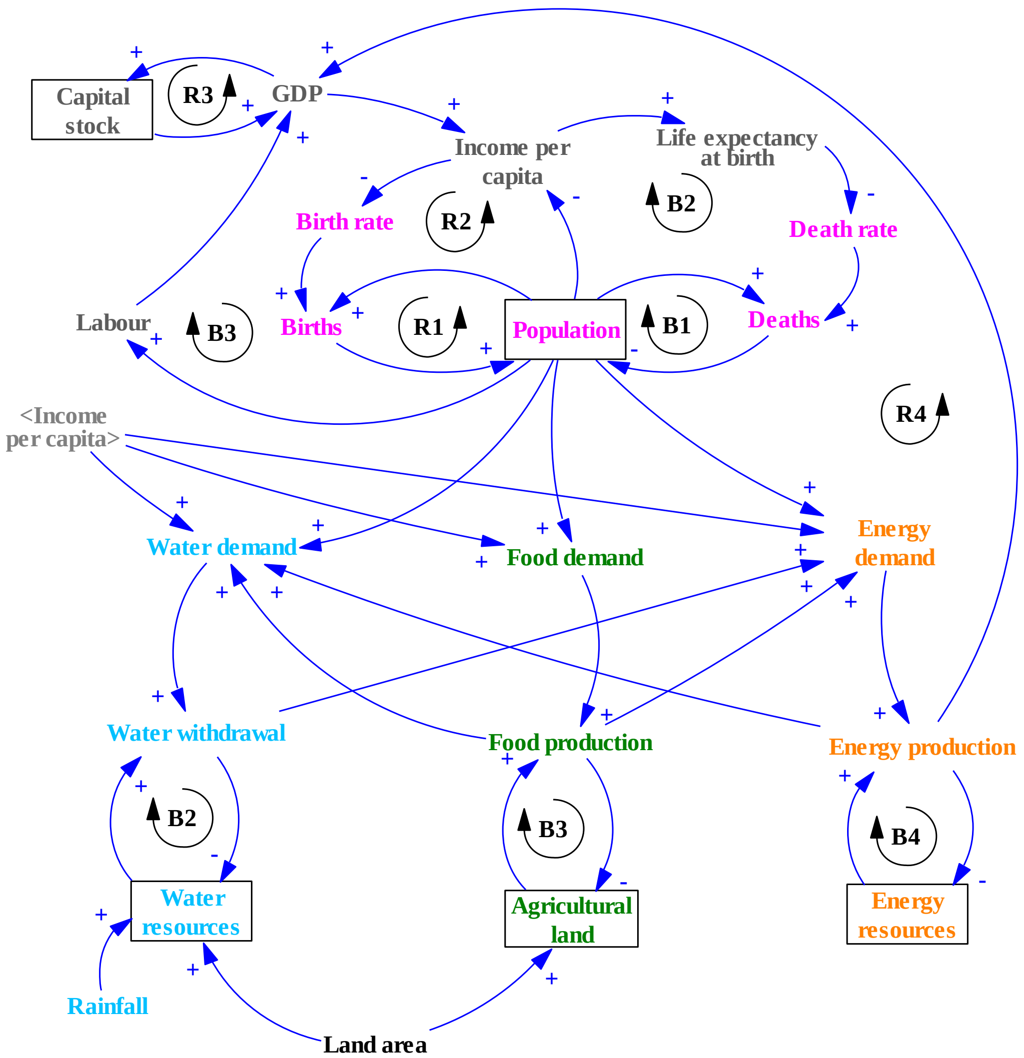


Figure 10 – System Model: Integrated Module

3.4. Model Experiment

Model experiment include model calibration, validation and scenario analysis. Actual or references data for calibration and validation were obtained from UN database, World Bank data, Indonesia Statistics and Ministry of Energy and Mineral Resource (MERM) of Indonesia.

3.4.1. Calibration and Validation

Model calibrations were carried out by adjusting model input parameters to minimise the difference between model output and the actual or reference data. Calibrations were carried out for each individual module and then for the integrated modules. Calibrated model was then validated against reference data using graphical comparison and error analysis.

For error analysis, we used Mean Squared Error (MSE) (equation 11), Root Mean Squared Percent Error (RMSPE) (equation 12), and the decomposition of MSE (equation 13 to 15):

$$MSE = \frac{1}{n}\sum(X_S - X_A) \quad (11)$$

$$RMSPE = 100 \cdot \sqrt{\frac{1}{n}\sum\left(\frac{X_S - X_A}{X_A}\right)^2} \quad (12)$$

$$U^M = \frac{(\overline{X_S} - \overline{X_A})}{MSE} \quad (13)$$

$$U^S = \frac{(S_S - S_A)}{MSE} \quad (14)$$

$$U^C = \frac{2(1-r)\cdot S_S \cdot S_A}{MSE} \quad (15)$$

where n is the length of data, X_S and X_A are simulated and actual data, $\overline{X_S}$ and $\overline{X_A}$ are mean value of simulated and actual data; S_S and S_A is standard deviation of simulated and actual data; r is coefficient of correlation between simulated and actual data; U^M is the fraction of MSE due to bias; U^S is fraction of MSE due to the unequal variance; U^C is the fraction of MSE due to unequal covariance.

The model is considered valid if one of these two conditions is met (Sterman, 1984):

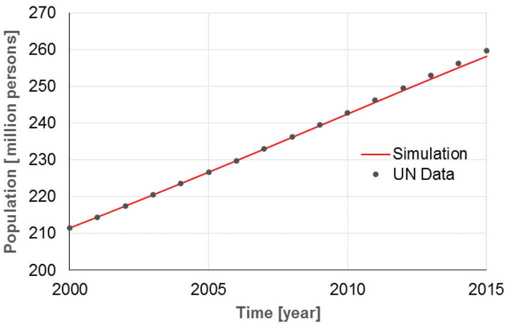
1. $RMSPE < 10\%$
2. $U^C > 50\%$ or $U^M + U^S \leq 50\%$

Table 3 shows statistical test results for simulated values of several model components. Graphical comparisons for these simulated values are presented in Figure 11.

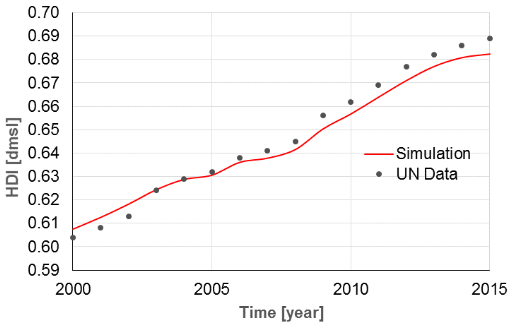
Most of the components pass set criteria for error analysis except beef demand, where it has percent error 17% above the set criteria, however it passes inequality test which is confirmed by the graphical comparison (Figure 11 (f)). Our model behaviour of beef demand shows similar trend of downward but cannot capture the wiggling part in the reference data.

Table 3 Error analysis results

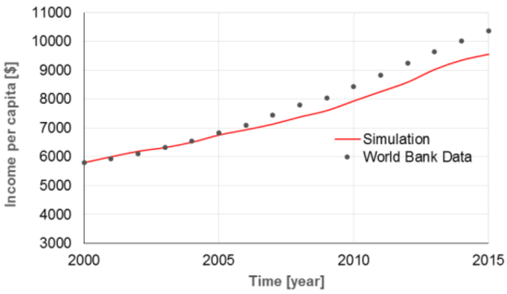
Components	Unit	***MSE*** **[unit²]**	***RMSPE*** **[%]**	U^m	U^c **[dmsl]**	U^s
Total population	*million person*	0.35816444	0.2341054	0.29902	0.54254	0.15845
HDI	*dmsl*	1.8887E-05	0.6618499	0.24147	0.62798	0.13055
Income Per Capita	*$*	190445.226	4.7826427	0.55712	0.41892	0.02396
Life Expectancy at Birth	*year*	0.05482469	0.3445307	0.55701	0.36108	0.08191
Domestic Water Demand	$10^9\ m^3$	0.04506629	1.3634738	0.59645	0.39435	0.0092
Electricity Production	*TWh*	5.55599966	1.7373286	0.57689	0.0003	0.42281
Electricity Demand	*TWh*	12.6106259	2.9805814	0.07301	0.64592	0.28107
Rice Demand	*kg/capita*	3.54331451	1.8063779	0.024	0.14576	0.83024
Beef Demand	*kg/capita*	0.00531133	17.276876	0.04903	0.22543	0.72554



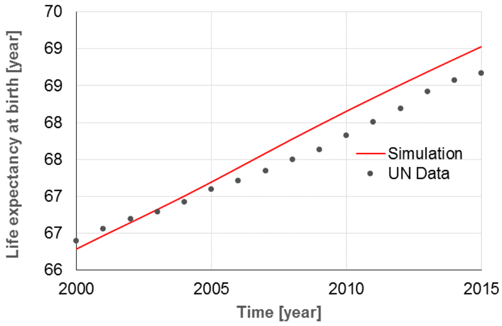
(a) population



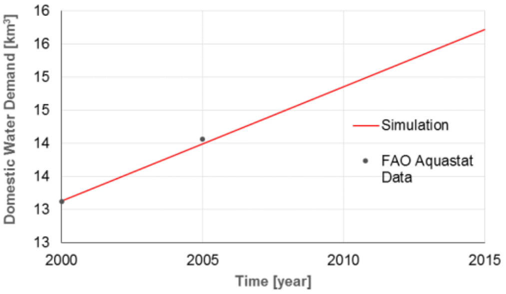
(b) HDI



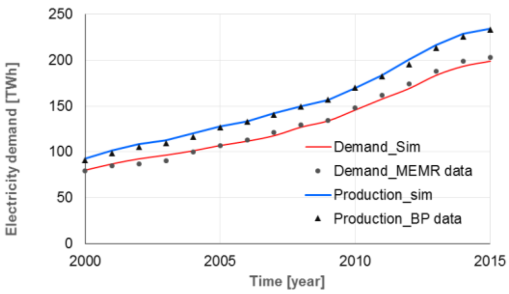
(c) Income per capita



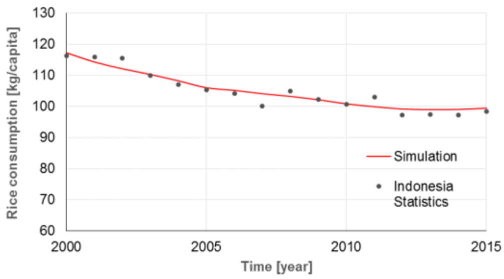
(d) Life expectancy at birth



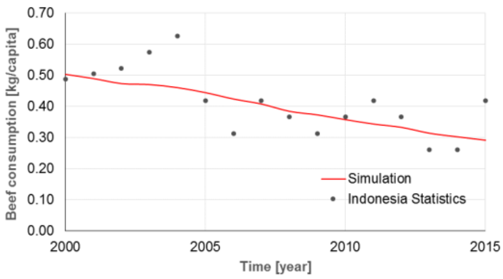
(e). Domestic water demand



(f) Electricity demand



(g) Rice demand

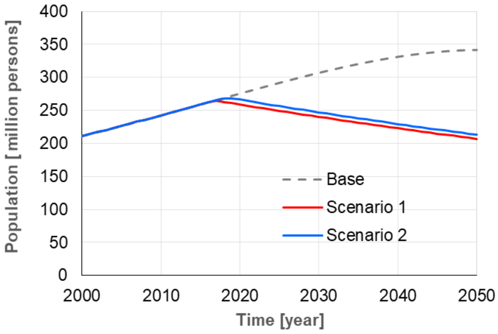


(h) Beef demand

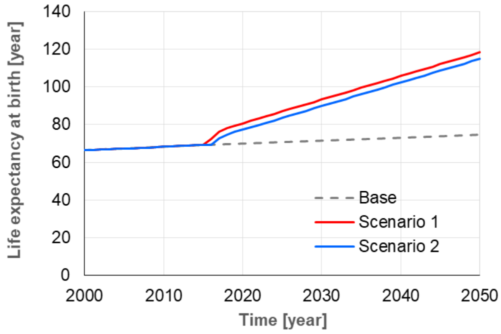
Figure 11 – Graphical comparison of model behaviour and reference data

3.4.2. Scenario Analysis

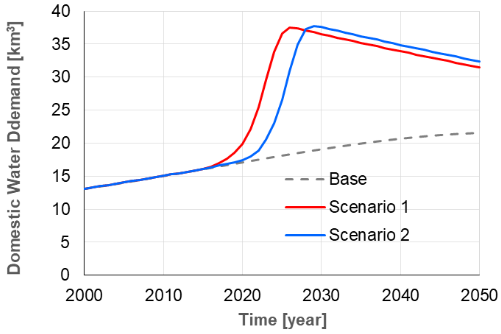
We run experiment with the model to learn how the system behave under certain scenarios. The first scenario is doubling the income per capita and second scenario is doubling the electricity demand. Both scenarios are implemented after year 2015 up to 2050. The results of the experiments for four affected components in our system model are shown in Figure 12.



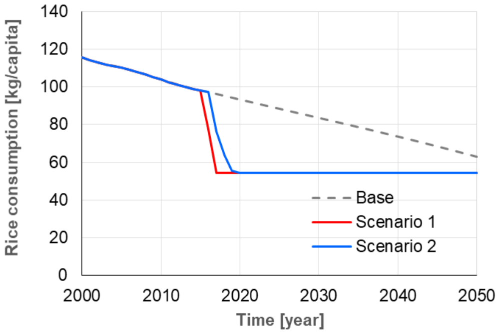
(a) Population



(b) Life expectancy at birth



(c) Domestic Water Demand



(a) Rice consumption

Figure 12 – Model scenario: scenario 1 = doubling income per capita, scenario 2 = doubling energy demand

It can be seen from the experiment results that our model system is sensitive to change on income per capita and energy demand. Similar departures in direction and magnitude from baseline for the outcome of population, life expectancy, water demand and rice demand are occurring on the two scenarios.

We can see that increasing income per capita will reduce population size even though it increases life expectancy at birth. This is because income per capita has strong impact on reducing birth rate than reducing death rate via life expectancy at birth. If concern is given to security of resources supply, then gaining more income per capita has positive impact on rice supply because it lowers rice demand but not for water supply because it increases domestic water demand.

4. Conclusions and Future Works

A study of water-food-energy nexus and the linkages to human development is being carried out. We have shown from literature that water, food and energy are interdependent and interplays with human development. We have also shown these interactions of water, food, energy and human development through modelling exercise. We used system dynamics modelling technique to explore the interlinkages and their consequences on the entire system. Simulated results of our model agreed with the actual data for the case of Indonesia. Two scenarios we carried out shown that changing income per capita and energy demand have significant impact on population, life expectancy at birth, domestic water demand and rice consumption.

However, for future works, sensitivity and uncertainty analysis are required to test how our system respond to changing in model parameters. We will also use this modelling assessment to experiment with the real policy scenarios that being set by government of Indonesia in order to learn how the system behave in the long run under such scenarios.

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