



Bridging Science and Policy in Water-Energy-Food Nexus: Using the Q-Nexus Model for Informing Policy Making

Ali Karnib¹

Received: 4 January 2018 / Accepted: 19 July 2018 /
Published online: 23 July 2018
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Abstract

Water, energy and food (WEF) systems are highly interconnected and they directly and indirectly affect one another. Science based tools that quantify the direct and indirect interconnections between water, energy and food systems are essential for informing effective WEF policy-making. The Q-Nexus Model is a mathematically-based quantitative WEF nexus assessment tool that serves as platform to quantify, simulate and optimize water, energy and food as interconnected systems of resources. This paper presents a generic scenario-based framework of using Q-Nexus Model for informing about the nexus effects that need to be reflected in the WEF planning and policy-making settings. Firstly, the technical features of the Q-Nexus Model and its capability to evaluate the direct and indirect quantitative effects are introduced. Secondly, the use of the Q-Nexus Model to quantify and simulate numerous key challenges and policy options are then presented. At the practical level, a numerical experiment is presented, and results are discussed. Lastly, the conclusions and further developments are presented.

Keywords Water-energy-food nexus · Q-nexus model · Sustainable development

1 Introduction

The interactions between water, energy and food systems should be considered in the planning and policy-making settings governing the management of these systems (Karnib 2017a, d; Hoff 2011; DTU 2016; Biggs et al. 2015; FAO 2013, 2014a, b, c). In fact, changes or actions on one system will lead to direct and indirect impacts on the other systems. Therefore, informing policy makers about the effects of the WEF interlinkages is crucial to ensure improved long-term outcomes of such changes and actions.

WEF nexus tools can be used to guide policy makers to simulate, quantify and optimize objectives representing their own interests (Karnib 2017a, b, c, d). Such models are necessary

✉ Ali Karnib
karnib.ali@gmail.com

¹ Lebanese University, Hadath Campus, Baabda, Lebanon

to support policy actions that will ensure sustainable and efficient production and use of WEF resources (Bizikova et al. 2013; FAO 2014c; Andrews-Speed et al. 2012; Waskom et al. 2014; Karnib 2016).

Many studies and scientific papers have been developed to explore and analyse the integrated nature of the water, energy and food systems (IRENA 2015; Hoff 2011; DTU 2016; Biggs et al. 2015; FAO 2013, 2014a, b, c; Karnib 2017a, b, c, d, e). A comprehensive list of the available WEF nexus tools can be found in IRENA (2015) and FAO (2014a, b, c). The existing tools and models are, either, addressing specific aspects of the nexus; or involving informing about the direct interlinkages across WEF systems, they are not engaging in analyzing the indirect impacts of interconnections.

A practical and science-based WEF nexus framework (the Q-Nexus Model) that addressing direct and indirect impacts is proposed by Karnib (2017a, b, c, d). This paper presents summary of the methodological aspects of the Q-Nexus Model and a generic scenario-based framework of using the model for informing effective WEF policy-making.

2 The Q-Nexus Model theory

The Q-Nexus Model is based on input-output theory and on the quantitative balance of the WEF use quantities. The quantities of the inter-sectoral use (z), the quantities of the end use (y) and the overall used quantities (x) ($x = z + y$) are the main quantitative conceptual elements of the model (Karnib 2017a).

In the Q-Nexus Model, the water, energy and food sectors are categorized by a set of inflows, such as, groundwater, surface water, wastewater reuse and desalination inflows that cover the water sector; similarly, the inflows of the energy sector may be, for example, the petroleum, electricity and renewable energy; and the food sector inflows may be the irrigated crops and other food production items. These inflows should be identified and organized based on the particular country or basin case study conditions.

If we denote by:

n , m and q the numbers of water, energy and food sectors inflows, respectively;

z_{ij}^{w-e} the water use for energy production;

z_{ij}^{w-f} the water use for food production;

z_{ij}^{e-w} the energy use for water production;

z_{ij}^{e-e} the energy use for energy production;

z_{ij}^{e-f} the energy use for food production;

z_{ij}^{f-e} the food use for energy production;

z_{ij}^{f-f} the food use for food production.

The WEF quantitative balance equations are formulated as follows (Karnib 2017a):

$$\sum_{j=1}^m z_{ij}^{w-e} + \sum_{j=1}^q z_{ij}^{w-f} + y_i^w = x_i^w \quad (i = 1, 2, \dots, n) \quad (1)$$

$$\sum_{j=1}^n z_{ij}^{e-w} + \sum_{j=1}^m z_{ij}^{e-e} + \sum_{j=1}^q z_{ij}^{e-f} + y_i^e = x_i^e \quad (i = 1, 2, \dots, m) \quad (2)$$

$$\sum_{j=1}^m z_{ij}^{f-e} + \sum_{j=1}^q z_{ij}^{f-f} + y_i^f = x_i^f \quad (i = 1, 2, \dots, q) \tag{3}$$

The water for water and food for water relations are considered quantitatively negligible and set equal to zero.

$y^w, y^e,$ and y^f represent the water, energy and food end use quantities, respectively. The end use of each sector will be decomposed into households demand, government demand, rest of the economy demand, losses, storage and exports. Taking the water sector as an example, if we denote by:

- y_i^{w-h} : the use of i^{th} water inflow for households demand;
- y_i^{w-g} : the use of i^{th} water inflow for government demand;
- y_i^{w-c} : the use of i^{th} water inflow for the rest of the economy demand;
- y_i^{w-l} : the losses of the i^{th} water inflow;
- y_i^{w-s} : the accumulation (storage) quantities of the i^{th} water inflow;
- y_i^{w-p} : the exported quantities of the i^{th} water inflow;

Then:

$$y_i^w = y_i^{w-h} + y_i^{w-g} + y_i^{w-c} + y_i^{w-l} + y_i^{w-s} + y_i^{w-p} \quad (i = 1, 2, \dots, n) \tag{4}$$

In the same manner the end use vector of energy and food sectors y_i^e and y_i^f , respectively, will be formulated as follows:

$$y_i^e = y_i^{e-h} + y_i^{e-g} + y_i^{e-c} + y_i^{e-l} + y_i^{e-s} + y_i^{e-p} \quad (i = 1, 2, \dots, m) \tag{5}$$

$$y_i^f = y_i^{f-h} + y_i^{f-g} + y_i^{f-c} + y_i^{f-l} + y_i^{f-s} + y_i^{f-p} \quad (i = 1, 2, \dots, q) \tag{6}$$

To transform the above balance equations into active WEF nexus model of interrelated resources that directly and indirectly affect each other, the following intensity-based coefficients are introduced:

$$\begin{aligned} a_{ij}^{w-e} &= \frac{z_{ij}^{w-e}}{x_j^e}, a_{ij}^{w-f} = \frac{z_{ij}^{w-f}}{x_j^f}, a_{ij}^{e-w} = \frac{z_{ij}^{e-w}}{x_j^w}, a_{ij}^{e-e} = \frac{z_{ij}^{e-e}}{x_j^e}, a_{ij}^{e-f} = \frac{z_{ij}^{e-f}}{x_j^f}, a_{ij}^{f-e} \\ &= \frac{z_{ij}^{f-e}}{x_j^e} \text{ and } a_{ij}^{f-f} = \frac{z_{ij}^{f-f}}{x_j^f} \end{aligned} \tag{7 - 14}$$

Where x_j^w, x_j^e, x_j^f are the total use of the j^{th} water sector inflow, total use of the j^{th} energy sector inflow and total use of the j^{th} food sector inflow, respectively.

These (a) coefficients represent the extents of resource inflows use in the production of other resources.

By introducing the intensity-based coefficients into eqs. (1, 2 and 3), they become:

$$\sum_{j=1}^m a_{ij}^{w-e} x_j^e + \sum_{j=1}^q a_{ij}^{w-f} x_j^f + y_i^w = x_i^w \quad (i = 1, 2, \dots, n) \tag{15}$$

$$\sum_{j=1}^n a_{ij}^{e-w} x_j^w + \sum_{j=1}^m a_{ij}^{e-e} x_j^e + \sum_{j=1}^q a_{ij}^{e-f} x_j^f + y_i^e = x_i^e \quad (i = 1, 2, \dots, m) \tag{16}$$

$$\sum_{j=1}^m a_{ij}^{f-e} x_j^e + \sum_{j=1}^q a_{ij}^{f-f} x_j^f + y_i^f = x_i^f \quad (i = 1, 2, \dots, q) \tag{17}$$

Equations (15, 16 and 17) can be written in simple form:

$$Ax + y = x \tag{18}$$

Or in block matrix form (Karnib 2017a):

$$\begin{bmatrix} 0 & A^{w-e} & A^{w-f} \\ A^{e-w} & A^{e-e} & A^{e-f} \\ 0 & A^{f-e} & A^{f-f} \end{bmatrix} \begin{bmatrix} x^w \\ x^e \\ x^f \end{bmatrix} + \begin{bmatrix} y^w \\ y^e \\ y^f \end{bmatrix} = \begin{bmatrix} x^w \\ x^e \\ x^f \end{bmatrix} \tag{19}$$

Finally, the total outputs (x) could be calculated for any end use values (y) using the following equation:

$$x = (I-A)^{-1}y \tag{20}$$

Where I is the identity matrix and $A = \begin{bmatrix} 0 & A^{w-e} & A^{w-f} \\ A^{e-w} & A^{e-e} & A^{e-f} \\ 0 & A^{f-e} & A^{f-f} \end{bmatrix}$ is the WEF nexus technology matrix (Karnib 2017a).

$(I-A)^{-1}$ matrix is known as the Leontief inverse or the total requirements matrix (Miller and Blair 2009), it captures in each of its elements direct and indirect impacts due to any change of the WEF sectors technology options and/or end use demands. The elements of this Leontief inverse matrix are often termed multipliers.

To illustrate the simulation innovation of the Q-Nexus Model, the following WEF intersectoral use intensities (t) and intersectoral allocation coefficients (c) are introduced (Karnib 2017b):

A simulation innovation was presented in (Karnib 2017b), which consists of introducing into the A matrix the intensities and the intersectoral inflows allocation coefficients as follows:

If the intensities of each inflow are denoted by (t)¹, then:

$$t_j^{w-e} = \frac{z_j^{w-e}}{x_j^e}; t_j^{w-f} = \frac{z_j^{w-f}}{x_j^f}; t_j^{e-w} = \frac{z_j^{e-w}}{x_j^w}; t_j^{e-e} = \frac{z_j^{e-e}}{x_j^e}; t_j^{e-f} = \frac{z_j^{e-f}}{x_j^f}; t_j^{f-e} = \frac{z_j^{f-e}}{x_j^e}; t_j^{f-f} = \frac{z_j^{f-f}}{x_j^f}; \tag{21 - 27}$$

If the intersectoral inflows allocation coefficients are denoted by (c), then:

$$\begin{aligned} c_{ij}^{w-e} &= \frac{z_{ij}^{w-e}}{z_j^{w-e}}; c_{ij}^{w-f} = \frac{z_{ij}^{w-f}}{z_j^{w-f}}; c_{ij}^{e-w} = \frac{z_{ij}^{e-w}}{z_j^{e-w}}; c_{ij}^{e-e} = \frac{z_{ij}^{e-e}}{z_j^{e-e}}; c_{ij}^{e-f} = \frac{z_{ij}^{e-f}}{z_j^{e-f}}; c_{ij}^{f-e} \\ &= \frac{z_{ij}^{f-e}}{z_j^{f-e}}; c_{ij}^{f-f} = \frac{z_{ij}^{f-f}}{z_j^{f-f}}; \end{aligned} \tag{28 - 34}$$

¹ Intensities may be referred also as “footprints”.

The technology matrix A was demonstrated in Karnib (2017b) as function of t and c to be as follows:

$$A = \begin{bmatrix} 0 & C^{w-e} \hat{t}^{w-e} & C^{w-f} \hat{t}^{w-f} \\ C^{e-w} \hat{t}^{e-w} & C^{e-e} \hat{t}^{e-e} & C^{e-f} \hat{t}^{e-f} \\ 0 & C^{f-e} \hat{t}^{f-e} & C^{f-f} \hat{t}^{f-f} \end{bmatrix} \tag{35}$$

Where,

\hat{t} is the diagonal matrix with the elements of the (t) along the main diagonal.

2.1 The direct and indirect effects

The WEF nexus are highly interconnected and they directly and indirectly affect each other. The nexus approach is used to model and evaluate these direct and indirect interactions. The key advantage that should characterize any WEF nexus model is its ability to evaluate the direct and indirect effects emerging from any change or action on any component of the WEF systems. This property must be considered as a basic feature to distinguish between nexus models and the other integrated assessment models.

To illustrate the direct and indirect interlinkage effects of the WEF nexus system, Fig. 1 shows the total water quantity calculated as the sum of the direct and all indirect water quantities required for any additional food demand.

As shown in Fig. 1, the additional demand for food requires direct inputs from water and energy sectors. Moreover, these water and energy quantities themselves require once again additional inputs from water and energy, which represent the first round of the indirect effects assessment; and so forth.

The WEF quantitative nexus approaches derive their importance from the fact that outputs are quantifying the combined effects of the direct and indirect impacts due to change in WEF end use demand and/or change in the technology used in the WEF intersectoral production system.

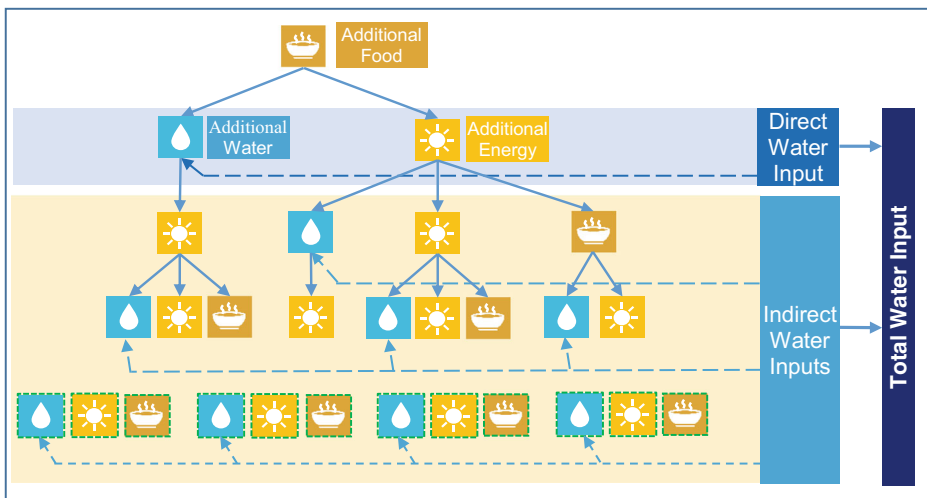


Fig. 1 Example of direct and indirect water quantities for additional food demand

Assuming that WEF production technology is unchanged, the Q-Nexus Model allows to evaluate the direct and indirect change in the intersectoral use quantities (ΔZ) and the total use quantities (Δx) for any change in end use values (Δy) by using the following equations (Karnib 2017a, d):

$$\Delta x = (I-A)^{-1}\Delta y \quad (36)$$

$$\Delta Z = A(I-\widehat{A})^{-1}\Delta y \quad (37)$$

Where.

$(I-\widehat{A})^{-1}\Delta y$ is the diagonal matrix with the elements of the $(I-A)^{-1}\Delta y$ along the main diagonal.

The direct and indirect repercussions in intersectoral use quantities (ΔZ_{direct}) and ($\Delta Z_{indirect}$) resulted from change in WEF end use demand as revealed in Fig. 1 above are demonstrated in Karnib (2017d) to be evaluated as follows:

$$\Delta Z_{direct} = A\widehat{\Delta y} \quad (38)$$

$$\Delta Z_{indirect} = A\widehat{\Delta Zu} \quad (39)$$

Where:

u is a unit column vector, whose elements are 1 used to generate row sums of the matrix ΔZ . $\widehat{\Delta Zu}$ is the diagonal matrix where the elements of the ΔZu are placed along the main diagonal.

2.2 WEF nexus indicators

A set of indicators are identified based on the methodological approach of the Q-Nexus Model. These indicators are clustered into quantity-based indicators, intensity-based indicators and allocation-based indicators. Table 1 shows the descriptions and equations of the proposed indicators for the water use in energy production (water for energy) and in food production (water for food). Similar type of indicators are used for the other intersectoral relationships between WEF resources, i.e., energy for water, energy for energy, energy for food, food for energy and food for food.

The use of the Q-Nexus Model theory to evaluate the values of the above-mentioned indicators will include the direct and indirect WEF interactions effects. The distinction between the direct and indirect effects values could be done using Eqs. (38) and (39).

2.3 Use of Q-Nexus Model for informing policy making

In this section, the use of the Q-Nexus Model for informing policy making will be introduced. Three categories of scenarios analysis will be performed: i) the first category consists of analysing scenarios related to change of end use demands or reducing end use losses; ii) the second category consists of analysing policies of adopting efficient technologies for the intersectoral use by considering “Best Practice” or “High Efficient” WEF production technologies; and iii) thirdly the model is used to simulate different water, energy and food

Table 1 Water for energy and water for food indicators of the Q-Nexus Model

	Description	Equation	Equation No.
Quantity-based indicators	Water use in the production of the j^{th} energy inflow	$z_j^{w-e} = \sum_{i=1}^n z_{ij}^{w-e}$	(40)
	Water use in the energy production	$z^{w-e} = \sum_{j=1}^m \sum_{i=1}^n z_{ij}^{w-e}$	(41)
	Water use in the production of the j^{th} food inflow	$z_j^{w-f} = \sum_{i=1}^n z_{ij}^{w-f}$	(42)
	Water use in the food production	$z^{w-f} = \sum_{j=1}^q \sum_{i=1}^n z_{ij}^{w-f}$	(43)
	Total intersectoral water use (in the energy and food production)	$z^w = z^{w-e} + z^{w-f}$	(44)
	Total water use	$x^w = z^w + y^w$	(45)
Intensity-based indicators	Intensity of water use in the production of the j^{th} energy inflow	$t_j^{w-e} = \frac{z_j^{w-e}}{x_j^e}$	(46)
	Intensity of water use in energy production	$s^{w-e} = \frac{z^{w-e}}{x^e}$	(47)
	Intensity of water use in the production of the j^{th} food inflow	$t_j^{w-f} = \frac{z_j^{w-f}}{x_j^f}$	(48)
	Intensity of water use in food production	$s^{w-f} = \frac{z^{w-f}}{x^f}$	(49)
	Allocation-based indicators	Proportion of water usage in the j^{th} energy inflow to the total water use in energy	$d_j^{w-e} = \frac{z_j^{w-e}}{z^{w-e}}$
Proportion of water use in energy to the total water use		$g^{w-e} = \frac{z^{w-e}}{x^w}$	(51)
Proportion of water usage in the j^{th} food inflow to the total water use in food		$d_j^{w-f} = \frac{z_j^{w-f}}{z^{w-f}}$	(52)
Proportion of water use in food to the total water use		$g^{w-f} = \frac{z^{w-f}}{x^w}$	(53)

intersectoral allocation policies and evaluate the performance of the WEF nexus systems. These three categories of scenarios analysis will be presented in sequence:

i) Variation of end use demand: the model allows to simulate scenarios of change of end use demand (Δy) and computing resulting change in intersectoral quantities (ΔZ) and total use quantities (Δx) as presented in Eqs. 36 and 37. A detailed application of the variation of end use demand to evaluate the WEF nexus in Lebanon is presented in Karnib (2017a).

ii) Adopting efficient technologies for intersectoral use: the Q-Nexus Model allows analysing policy options of adopting high efficient WEF production technologies by changing the production intensities (t). High efficient technology matrices could be proposed using Eq. 35 which reflect the WEF intersectoral production alternatives using most efficient technologies at present. A comprehensive application of the variation of intersectoral use technologies for the WEF nexus in Lebanon is presented in Karnib (2017b).

iii) Scenarios proposed based on change of WEF intersectoral allocation policies: In quantitative WEF nexus systems, different water and energy inflows are used to produce water, energy and food supplies. For example, different water sources (i.e. groundwater, surface water, desalination ...) may be used in electricity and food production. The Q-Nexus Model allows to consider different water and energy allocations options in WEF sectors by changing the intersectoral inflows allocation coefficients (c), therefore, technology matrix alternatives could be then proposed using Eq. 35. A detailed numerical experiment of analysing WEF intersectoral allocation policies could be found in Karnib (2017c).

Figure 2 summarise the potential simulation input variables and output indicators of the Q-Nexus Model.

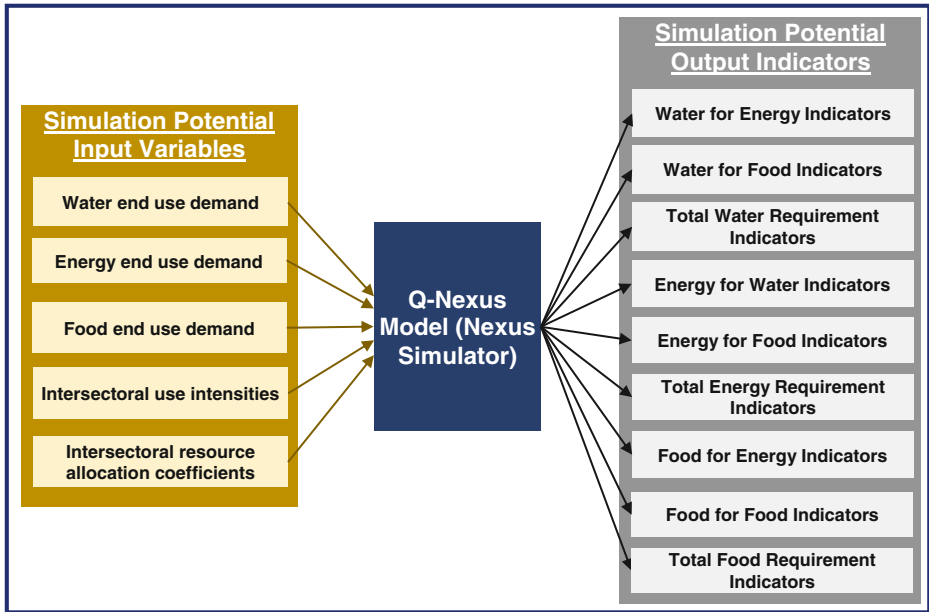


Fig. 2 The simulation potential input variables and potential output indicators of the Q-Nexus Model

Figure 3 presents a generic scenario-based framework of using Q-Nexus Model for informing policy making. The identified related input variables of challenges and policy options serve as input to the nexus simulation model; and when processed, selected output indicators will be used to inform policy making.

Table 2 presents examples of WEF nexus challenges (or tensions) and the related input variables of the Q-Nexus Model. Moreover, Table 3 presents examples of WEF nexus policy options and the related input variables of the Q-Nexus Model.

While the presented scenario-based framework of using Q-Nexus Model for informing policy making is generic in nature, analyses of challenges and policy options (solutions) must be specific to the area/country for which the solutions are sought. Therefore, the examples of challenges and solutions mentioned above are not exhaustive, many other challenges and

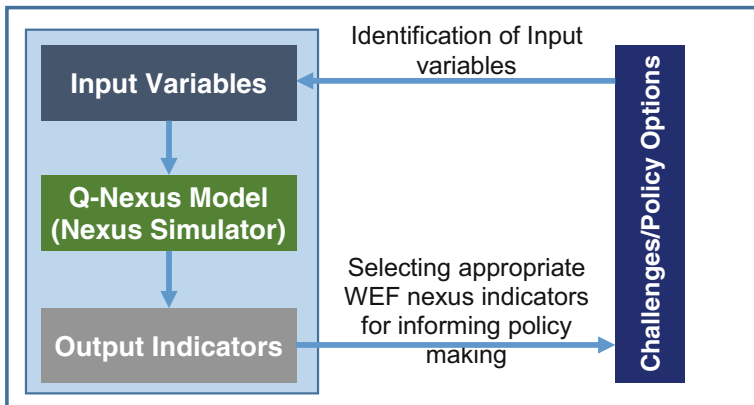


Fig. 3 Generic scenario-based framework of using Q-Nexus Model for informing policy making

Table 2 Examples of WEF nexus challenges/tensions scenarios and the related input variables of the Q-Nexus Model

Challenges/tensions	Identified Input variables of the Q-Nexus Model
Increasing water demand	y_i^w
Increasing energy demand	y_i^e
Increasing food demand	y_i^f
Reducing of cultivated lands	y_i^f
Reducing irrigated agriculture	y_i^f
Change in water allocation	c
Change in cropping type/pattern	y_i^f, t, c

solutions and their related Q-Nexus Model input variables could be identified based on the particular challenges or solutions that are applicable to the area/country under study.

Pairing WEF nexus simulator with policy making can be used beneficially for the evaluation of policy options and can provide key insights for policy makers. The nexus simulator can be used to execute the WEF nexus simulation many times which allows policy makers to analyze changes in the WEF nexus input variables and calculate the changes occurred in WEF sectors. This will allow policy/decision makers to examine valuable information that the simulation model may generate.

3 Illustrative Example and Analysis Of Results

A hypothetical case study of a WEF nexus system consistent with Lebanon setting will be presented to elucidate the Q-Nexus Model features for informing policy making where the entire series of direct and indirect effects will be evaluated. The following WEF inflows are considered:

- Water sector inflows (W) (Mm³/year): 1) surface water; 2) groundwater; 3) desalination; 4) wastewater reuse; 5) agricultural drainage and recycled water reuse. The values of energy use in these water inflows include water extraction, treatment, conveyance and distribution.

Table 3 Examples of WEF nexus policy options and the related input variables of the Q-Nexus Model

Policy options (solutions)	Identified Input variables of the Q-Nexus Model
Reuse of wastewater and drainage water	y_i^w, c
Increasing water use efficiency in different water uses	t
Modernize and improve sustainability of agricultural infrastructure and production	t
Promote renewable energy sources	y_i^e, t, c
Change in food crop productivity	y_i^f, t
Technology change in energy production	y_i^e, t, c
Change in resources allocation policies	c
Reduce losses and wastes	y_i^f, t
Making use of trade	y_i^p

Table 5 Intersectoral and total water and energy use of the BAU scenario

z^w (Mm ³ /year)	x^w (Mm ³ /year)	z^e (ktoe/year)	x^e (ktoe/year)
1486	1900	947	6104

- Energy sector inflows (E) (ktoe/year): 1) petroleum; 2) electricity (petroleum); 3) electricity (hydro); 4) electricity (wind/solar); 5) biofuels. These inflows are evaluated in terms of primary energy equivalent on a net calorific value basis.
- Food sector inflows (F) (kt/year): 1) irrigated cereals; 2) irrigated roots and tubers; 3) irrigated vegetables; 4) irrigated fruits; 5) Other Agriculture, Forestry & Food products. These inflows are evaluated by including agriculture, food processing, transportation and storage.

Table 4 presents the WEF intersectoral use values ($z_{ij}^{w-e}, z_{ij}^{w-f}, z_{ij}^{e-w}, z_{ij}^{e-e}, z_{ij}^{e-f}, z_{ij}^{f-e}, z_{ij}^{f-f}$) and the corresponding end use values ($y_i^h, y_i^g, y_i^c, y_i^l, y_i^s, y_i^p$). These values represent the Business as Usual (BAU).

The resulting effects on water and energy use (direct and indirect) will be analyzed as consequences of the following challenges and policy options scenarios:

- Scenario 1 (challenges scenario): This scenario consists of increasing 20% the household end use demand of water, energy and food due to population growth. All other end use demands, WEF production intensities and allocation coefficients are assumed unchanged.
- Scenario 2 (policy options scenario): This scenario consists of: i) reducing 20% of the water losses of the water end use; and ii) decreasing 20% the water use intensities (t_j^{w-f}) of the food production inflows which means increasing water use efficiency in food production (the energy use intensities for food production are assumed unchanged).
- Scenario 3 (combination of scenario 1 and scenario 2): The positive and negative impacts resulted from scenarios 1 and 2 will be analyzed. This scenario shows how negative effects of scenario 1 could be offset by the positive effects of scenario 2 within the nexus approach framework where the direct and indirect impacts of challenges and policy alternatives are calculated.

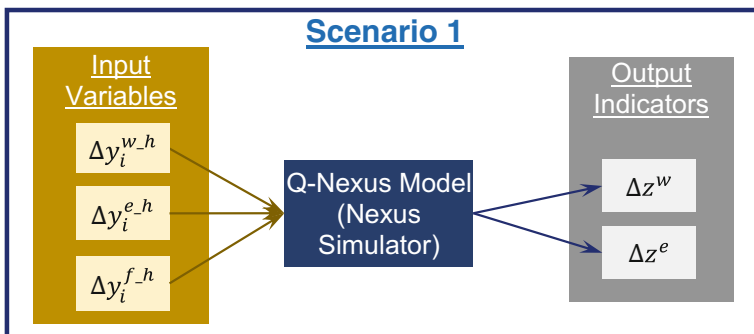


Fig. 4 The selected input variables and output indicators of the Q-Nexus Model used for scenario 1

Table 6 Additional intersectoral water use (Δz^w) and energy use (Δz^e) resulted from scenario 1

	Δz^w	Δz^e
Direct	145.25	79.62
Indirect	8.99	21.23
Total	154.24	100.85

The required water and energy (quantitative-based indicators) will be used for informing policy makers about the effects of the above-mentioned scenarios.

The intersectoral water and energy use (z) and the total water and energy use (x) for the BAU scenario are shown in Table 5.

Simulation results of scenario 1:

The resulting change in the water and energy intersectoral use (Δz^w) and (Δz^e) caused by the additional household end use demand (Δy_j^h) are assessed using the Q-Nexus Model simulator. Figure 4 presents the selected input variables and output indicators of the Q-Nexus Model used for scenario 1. The results of the direct, indirect and total resource requirements are presented in Table 6.

The intersectoral water resources will have to increase its direct output by $\Delta z_{direct}^w = 145.25 \text{ Mm}^3$, similarly, intersectoral energy resources will have to increase its direct output by $\Delta Z_{direct}^e = 79.62 \text{ ktoe}$, but then, these new direct intersectoral values require to produce additional indirect intersectoral water and energy quantities. Ultimately, water will have to increase its total outputs (direct and indirect) by $\Delta Z^w = 154.24 \text{ Mm}^3$. Similarly, the energy sector should increase its total outputs (direct and indirect) by $\Delta Z^e = 100.85 \text{ ktoe}$.

Simulation results of scenario 2:

The BAU water use intensities in food production inflows (t_j^{w-f}) are shown in Table 7. The newly examined water use intensities for scenario 2 are shown in Table 8.

In addition to the increasing of the water use efficiencies, this scenario considers also a reduction of 20% of the end use water losses which are amounted at $35.60 \text{ Mm}^3/\text{year}$. Figure 5 presents the selected input variables and output indicators of the Q-Nexus Model used for scenario 2.

This scenario reduced the total water requirement (direct and indirect) by $\Delta x^w = 288.09 \text{ Mm}^3/\text{year}$ compared to BAU scenario. As consequence of the reduction of water requirement, the intersectoral energy requirement (direct and indirect) will be reduced by $\Delta x^e = 44.69 \text{ ktoe}$, which indicates that policies of scenario 2 have positive impacts on water availability and stress.

Simulation results of scenario 3:

Figure 6 presents the selected input variables and output indicators of the Q-Nexus Model used for scenario 3.

Table 7 The BAU water use intensities in food production inflows (t_j^{w-f}) in m^3/kg

F1	F2	F3	F4	F5
1.26	0.49	0.19	0.55	0.13

Table 8 The water use intensities considered in food production inflows for scenario 2 (t_j^{w-f}) in m^3/kg

F1	F2	F3	F4	F5
1.01	0.39	0.16	0.44	0.10

Table 4 The intersectoral use and end use of WEF inflows

	W1	W2	W3	W4	W5	E1	E2	E3	E4	E5	F1	F2	F3	F4	F5	End Use	y_i^h	y_i^g	y_i^c	y_i^i	y_i^j	y_i^k
W1	0.0	0.0	0.0	0.0	0.0	40.0	110.0	20.0	0.5	1.0	120.0	110.0	100.0	180.0	300.0	30.0	30.0	1.0	4.0	28.0	0.0	1.0
W2	0.0	0.0	0.0	0.0	0.0	20.0	30.0	0.0	0.5	1.0	65.0	55.0	60.0	90.0	150.0	154.0	154.0	2.0	16.0	146.0	0.0	2.0
W3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.0	14.0	0.0	12.0	4.0	0.0	0.0
W4	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	5.0	5.0	5.0	5.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
W5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	2.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
E1	10.0	12.0	10.0	5.0	5.0	0.0	0.0	0.0	0.0	0.0	100.0	60.0	70.0	80.0	150.0	1000.0	90.0	336.0	470.0	0.0	0.0	0.0
E2	80.0	110.0	25.0	2.0	1.0	0.0	0.0	0.0	0.0	0.0	40.0	20.0	30.0	30.0	70.0	1400.0	160.0	1071.0	465.0	0.0	0.0	0.0
E3	1.0	1.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	5.0	5.0	5.0	5.0	50.0	5.0	30.0	15.0	0.0	0.0	0.0
E4	1.0	2.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	1.0	0.0	4.0	0.0	0.0	0.0	0.0
E5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	60.0	0.0	0.0	0.0	0.0	0.0	0.0
F1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.0	80.0	1.0	10.0	1.0	1.0	2.0	50.0
F2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	228.0	0.0	10.0	2.0	10.0	2.0	102.0
F3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	600.0	1.0	225.0	0.0	2.0	2.0	26.0
F4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	2.0	72.0	2.0	40.0	2.0	292.0
F5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	160.0	0.0	0.0	0.0	0.0	15.0	2000.0	200.0	300.0	100.0	60.0	60.0	789.0

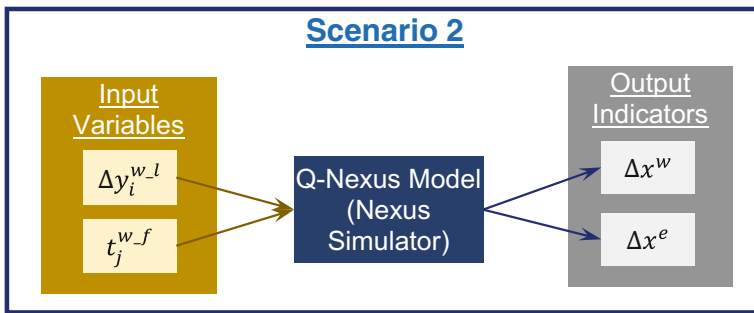


Fig. 5 The selected input variables and output indicators of the Q-Nexus Model used for scenario2

The resulting value of the total water use (direct and indirect) $x^w = 1779.20 \text{ Mm}^3/\text{year}$ which is less than the value of the BAU scenario ($1900 \text{ Mm}^3/\text{year}$).

4 Discussion

The challenges of scenario 1 have negative impacts on the water availability and water stress. The results of the simulation can inform policy makers about the additional direct and indirect water and energy requirements if the BAU resource production technology and allocation are remain unchanged. To reduce water stress, challenges of scenario 1 should be combined with policies to increase water availability. Policy makers should examine policy options such as increasing the safely wastewater reuse, increasing water use efficiency, increasing the safely agricultural drainage water reuse and reducing water losses.

The policy options analysis of scenario 2 using the Q-Nexus Model shows that reducing water losses and increasing water use efficiency in food production will lead to positive impacts on water availability when compared to BAU scenario.

The simulation results of scenario 3 permit to inform policy makers on how the negative impacts of the challenges of scenario 1 on water availability may be offset by the positive impacts of the policy options of scenario 2 in a framework of nexus approach where the direct and indirect effects of challenges and policy options are calculated.

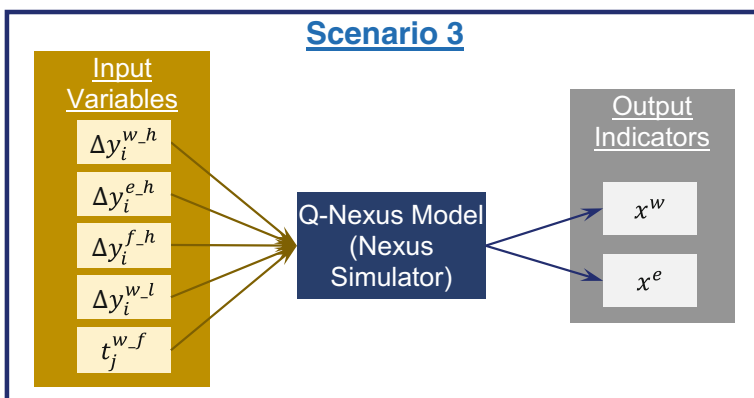


Fig. 6 The selected input variables and output indicators of the Q-Nexus Model used for scenario 3

As shown in this example, policy makers can, based on the considered challenges or policy options, select the related input variables, run the Q-Nexus Model simulator and use the relevant output indicators that provide the appropriate information to ensure improved long-term outcomes of such challenges and actions.

It is important to mention that the Q-Nexus Model helps policy makers in performing quick analysis and assessment by evaluating the direct and indirect WEF resource requirements for any considered challenge or policy option. Such quick assessment would inform policy makers towards the orientations in which deep analysis would be needed.

5 Conclusions and Further Developments

Effective water, energy and food policy making necessitates the adoption of scenario assessment framework supported by science based WEF nexus simulation and assessment tools that are able to evaluate the direct and indirect WEF resource requirements for any considered challenge or policy option. This paper presented a generic scenario-based framework of using Q-Nexus Model for informing about the nexus effects that need to be reflected in the WEF planning and policy-making settings. The theory of the Q-Nexus Model and its capability to evaluate the direct and indirect quantitative effects are introduced. The ability of the Q-Nexus Model to quantify and simulate large set of WEF nexus challenges and policy options are also presented. These may include scenarios of resources demand change, production technology change and/or production allocation change. A set of challenges and policy options are listed and the related Q-Nexus Model input variables and output indicators are identified. Finally, an example of three WEF nexus challenges and policy scenarios is presented showing model outputs used as support for guided management policy making strategies.

Using the Q-Nexus Model offers an example on how to bring inputs from science to inform policy-making to converge toward effective planning and development of WEF systems. Further works need to be done to improve the model by including the economic and ecosystems challenges within the nexus analysis. This will permit to move towards a nexus approach for informing the sustainable development in effective way. This issue is still under development at our university.

Acknowledgements An initial shorter version of the paper has been presented at the 10th World Congress of EWRA “Panta Rhei”, Athens, Greece, 5-9 July 2017.

Compliance with Ethical Standards

Conflict of Interest None.

References

- Andrews-Speed P, Bleischwitz R, Boersma T, Johnson C, Kemp G, VanDeveer SD (2012) The global resource nexus: the struggles for land, energy, food, water, and minerals. Transatlantic Academy, Washington DC
- Biggs EM, Bruce E, Boruff B, Duncan J, Horsley J, Pauli N, McNeill K, Neef A, Van Ogtrop F, Cumow J, Haworth B, Duce S, Imanari Y (2015) Sustainable development and the water-energy-food nexus: A perspective on livelihoods. *Environmental Science & Policy Journal* 54:389–397

- Bizikova L, Roy D, Swanson D, Venema HD, McCandless M (2013) The water-energy-food security nexus: towards a practical planning and decision-support framework for landscape investment and risk management. International Institute for Sustainable Development (IISD), Winnipeg
- FAO (2013) An innovative accounting framework for the food-energy-water Nexus, Environment and Natural Resources Management. Food and Agriculture Organisation of the United Nations, Working Paper No. 56, Rome
- FAO (2014a) The Water-Energy-Food Nexus at FAO. Food and Agriculture Organisation of the United Nations, Concept Note, Rome
- FAO (2014b) Walking the Nexus Talk: Assessing the Water-Energy-Food Nexus in the Context of the Sustainable Energy for All Initiative. Food and Agriculture Organisation of the United Nations, Rome
- FAO (2014c) The water-energy-food nexus - a new approach in support of food security and sustainable agriculture. Food and Agriculture Organization of the United Nations, Rome
- Hoff H (2011) Understanding the Nexus. Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environment Institute (SEI), Stockholm
- IRENA (2015) Renewable energy and the water, energy and food nexus. IRENA Web. http://www.irena.org/documentdownloads/publications/irena_water_energy_food_nexus_2015.pdf. Accessed December 2017
- Kamib A (2016) A methodological approach for sustainability assessment: application to the assessment of the sustainable water resources withdrawals. *International Journal of Sustainable Development, Inderscience Publishers* 19(4):402–417
- Kamib A (2017a) Quantitative assessment framework for water, energy and food nexus. *Computational Water, Energy, and Environmental Engineering Journal, Scientific Research Publishing Inc* 6:11–23
- Kamib A (2017b) Evaluation of technology change effects on quantitative assessment of water, energy and food nexus. *Journal of Geoscience and Environment Protection, Scientific Research Publishing Inc* 5:1–13
- Kamib A (2017c) Water-Energy-Food Nexus: A Coupled Simulation and Optimization Framework. *Journal of Geoscience and Environment Protection, Scientific Research Publishing Inc* 5:84–98
- Kamib A (2017d) Water, Energy and Food Nexus: The Q-Nexus Model. *European Water* 60:89–97
- Kamib A (2017e) A Quantitative Nexus Approach to Analyze the Interlinkages across the Sustainable Development Goals, *Journal of Sustainable Development. Canadian Center of Science and Education* 10(5):173–180
- Miller RE, Blair PD (2009) Input-output analysis. Foundations and extensions. Cambridge University Press, Cambridge
- Technical University of Denmark (DTU) (2016) The Energy-Water-Food Nexus - from local to global aspects. DTU Web. http://www.natlab.dtu.dk/english/energy_reports/dier_2016. Accessed January 2017
- Waskom R, Akhbari M, Grigg N (2014) U.S. Perspective on the Water-Energy-Food Nexus. Colorado Water Institute, Completion Report No.116, Colorado