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The conceptual framework to determine interrelations and interactions for holistic Water, Energy, and Food Nexus

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Abstract

Several models with a variety of concepts and approaches have been proposed to address different aspects of the Water-Energy-Food (WEF) nexus system. In some models, the interaction between WEF resources is considered without considering the internal relationships between subsystems and vice versa. This is while, a comprehensive model should consider all internal and external relationships between the three subsystems which are named interrelations and interactions, respectively. Therefore, this study was an initial step to introduce the holistic WEF nexus simulator framework and its components. In a holistic model, it is axiomatic that extensive data should be gathered. Hence, in the second step, the authors attempted to classify the huge amount of required data into two distinct categories: (1) non-simulated data (independent parameters, independent variables, and management parameters) and (2) simulated data (IFs and THENs). In addition to providing valuable feedback on the WEF nexus concept and providing required data for policy evaluation and assessment, listing and classifying the required data and describing them in terms of IFs and THENs will provide valuable insight. This study shows how extensive data can be accessed and shared within a comprehensive nexus simulation model. As a result of using this classification method, the interrelations between each subsystem and the interactions with other subsystems in the nexus model can be extracted simply, and none of them will be overlooked due to lack of knowledge about the nexus system. Additionally, these IFs and THENs variables are considered as a great solution to diminish the complexity of the nexus system to implement it.

Keywords Energy Security · Food Security · Nexus Simulation Model · Water-Energy-Food Nexus · Water Security

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1 Introduction

Water-Energy-Food (WEF) demand is being augmented at an astonishing rate by drivers such as urbanization, climate change, and population growth. Compared to 2015, it has been predicted that WEF demand will increase by almost 50% until 2050 (de Amorim et al., 2018; IRENA, 2015; UN, 2012). WEF subsystems worldwide will be adversely affected by this, so the main resources will be put under immense stress. WEF subsystems are inextricably linked to one another. On account of heightened water supply stress, severe droughts, which are exacerbated by climate change, can pose serious problems for energy and food security (Adebiyi et al., 2021; Zhang et al., 2018; Molajou et al., 2021c). As a result of the water stress imposed by the increased demand for all resources, it is predicted that 700 million people will migrate to other regions. War will be the inevitable result of water scarcity (UN, 2019).

Various methods of managing resources individually were applied in previous decades. For example, the Integrated Water Resources Management (IWRM) was previously used to manage water resources. Water is the focus of this approach, as other resources are measured in relation to water (Bach et al., 2012). The Twin-Track approach to agriculture, on the other hand, was developed in 2000 by the Food Agricultural Organization (FAO) (Broca, 2002; FAO, 2003; Pingali et al., 2005). Even though both of these approaches attempted to improve the status of resources, the management strategy adopted couldn't account for the synergies and effects between the resources. As a result, these strategies did not consider the interconnections among resources. Therefore, to achieve robust management methods to have sustainable resources, it is imperative to have a paradigm shift that can assess the resources simultaneously (D'Odorico et al., 2018; Daher & Mohtar, 2015; Wu et al., 2021). The new management method is called the WEF nexus approach.

The concept of the WEF nexus was put forward sincerely so that the global resource systems would be investigated and managed in a coordinated manner (Rasul, 2016; Smajgl et al., 2016; Yillia, 2016). The "nexus" word is derived from "nectere," which means "to link" in Latin and refers to the study of something connected to something else. Hence, the WEF nexus focuses on the interactions between water and energy subsystems, as well as food subsystems. The nexus approach is determined to supply a dynamic and cross-sectoral standpoint, which helps us better perceive the dynamic and complex interactions among WEF subsystems to utilize and manage our limited resources in a sustainable manner. In addition, it allows us to consider the synergies and impacts of sectoral decisions that extend beyond the specific sector (Bazilian et al., 2011; FAO, 2014b; Hoff, 2011).

WEF nexus approach is according to the opinion that it's more likely impossible to achieve WEF security without considering interdependencies between them. For instance, water is needed in the food subsystem to irrigate crops, and this amount of water requires energy to be pumped, delivered, treated, collected, and distributed. On the other hand, a large amount of water is needed in a thermal power plant's cooling system to generate electricity and other energy carriers. Water is also necessary for both the extraction and processing of fossil fuels. In addition, water and energy are important to agricultural lands so that food can be produced, processed, packaged, stored, and transported (De Laurentiis et al., 2016; Park & Kim, 2019; Sadeghi et al., 2020; Xu et al., 2020; Zaman et al., 2017).

One of the major shortcomings of the WEF nexus system is that policymakers and decision-makers do not have the appropriate tools to evaluate different resource allocation strategies. Understanding and accurately recognizing the relationships between the various elements of the WEF nexus system and, as a result, modeling their interactions can be a useful tool for managers and decision-makers to make accurate and appropriate decisions about how to address the challenges between diverse stakeholders (Wu et al., 2021).

The WEF nexus has been the subject of several models with different approaches that claim they can quantify the interaction between components (FAO, 2014a, 2014b; IRENA, 2015). These nexus models have been focused on external relations between resources, which is called interaction. The WEF Nexus Tool 2.0, developed by Daher and Mohtar (2015), Water–Energy–Food Nexus Simulation WEFSiM by Wicaksono and Kang (2019), and WEF-Ecosystems Nexus (WEFE Nexus) by Malagó et al. (2021) to examine the interactions between WEF sources is a clear example of this approach. Additionally, other modeling approaches have been used for nexus in recent years. In this approach, internal relations are thoroughly explored in each subsystem, but all models must be linked to study interactions. It has been found that this approach is not well received due to the complexity of linking models. A hybrid model such as WEAP-LEAP can also be used for this approach (Javadifard et al., 2020).

2 Literature review

The WEF nexus has been interpreted and quantified using several simulation models on various scales. Several simulation models have been developed to quantify nexus patterns at the national, regional, and local levels, including the WEF Nexus Tool 2.0 (Daher & Mohtar, 2015), MuSIASEM (Giampietro et al., 2009), and NexSym (Martinez-Hernandez et al., 2017). The analysis of several existing nexus frameworks revealed that the different significant data of WEF was not adequately considered in the existing models (Wicaksono et al., 2017, 2019). In the ANEMI model, eight major components comprise the carbon cycle, population, water use, society-biosphere-climate system, land use, surface water flow, water quality, and economy, and the way in which interactions or feedbacks between them determines the behavior of the system. This model couldn't consider the necessary and primary data that was needed in the WEF nexus model (Davies & Simonovic, 2010). In 2012, the WEF Nexus Tool 2.0 was developed, and most of the previous model's problem was solved. Water, energy, and farmland requirements are calculated in Nexus Tool 2.0, which supports the self-sufficiency of food products, but limited feedback analysis is provided between resources (Daher & Mohtar, 2015). In the Nexus Tool 2.0, all interrelations are considered based on balance equation that it means most of the effective interrelations which can alter interactions are neglected. A couple of years later, the NexSym model was developed to consider major interactions and primary required data. The NexSym comprises a more comprehensive analysis but only allows simulation at the local scale (Martinez-Hernandez et al., 2017), and it does not take into account the most important demand side's data. On the other hand, MuSIASEM also simulates the WEF nexus with an emphasis on external components, including land, economy, human capital, ecosystems, greenhouse gas emissions, and land use, utilizing Georgescu-Roegen's flow-fund elements approach (Giampietro et al., 2009). This model could not consider and categorized the energy subsystem's data in the context of the WEF nexus.

In 2019, the WEFSiM model was developed by Wicaksono et al. (2019). Based on this study, it appears that WEF nexus simulations using optimization can improve the models dedicated to managing limited resources. This model almost partially covered the shortcomings of previous models such as WEF Nexus Tool 2.0 and NexSym. In other words, the supply and consumption side of this simulation approach was modeled correctly.

Regardless of all advantages, the model failed to distinguish between simulated and non-simulated data, thus increasing the complexity of the model. Within a few years, a model was developed similar to WEFSiM, which is applicable to Saskatchewan, Canada, and is called WEF-Sask (Wu et al., 2021). WEF-Sask is an integrated WEF nexus model that was developed to gain insights into these issues using a system dynamics approach that incorporated both the production and demand sides of WEF subsystems. Besides being capable of integrated resource management, the model structure is generic and can be readjusted to fit other regions as well. In the model results, it is shown that the WEF sectors are all affected differently by socioeconomic and climate factors. This model was more complete than the WEFSiM model in terms of a data structure but could not reduce the complexity of the model by categorizing simulated and non-simulated data. Another model was developed in 2021, which is called WEFE Nexus (Malagó et al., 2021). It was developed an analytical framework for analyzing the impact on 17 sustainable development goals, and it quantified the extent of the connection between nexus pillars and sustainable development goals explicitly. Renewable energies play an important role in achieving sustainability, according to the findings. It is noteworthy that this model couldn't consider the important interaction and interrelation data to demolish the complexity of the model.

Further, WEF nexus models need to be modeled holistically, so they can take into account the vast majority of the interactions between components in each subsystem, as well as interrelations among them (Molajou et al., 2021a, 2021b). By using IFs and THENs variables, the study proposes a novel strategy for identifying all interactions and interrelations for a holistic WEF nexus simulator. Consequently, interactions and interrelations in the nexus system can be recognized and clarified better, so the complexity of the nexus can be reduced. With regard to this classification, outputs of each subsystem can be determined by the inputs which are received from other subsystems. It is extremely useful to develop and evaluate different scenarios based on this insight since the alternation of subsystems is more recognizable.

3 Materials and method

The holistic WEF nexus approach not only should be able to analyze multiple scenarios but also should be efficient, resilient, and generalized, which can lead to the development of a wealth of strategies that make policymaking easier. In this way, three holistic modules are defined for WEF subsystems by considering an interdisciplinary and integrated view of nexus, as well as focusing on how whole components interact with each other. By implementing the nexus approach, each module can be simulated in a stand-alone way as well as taking into account how they interact. The schematic overview in Fig. 1 illustrates the framework and its major components of the holistic WEF nexus simulator.

As can be seen in Fig. 1, the relations that exist within the system boundary of each subsystem are called interrelations. In addition to the interrelations, the nexus system also has another relationship called interaction, which refers to the mutual impact of one subsystem on another. Interactions and interrelations affect one another. As an illustration, the evaporation from the reservoir is considered as an interrelation in the water subsystem, and the hydraulic head in the reservoir is considered as an interaction between the water subsystem (reservoir) and energy subsystem (hydropower). The amount of evaporation in the reservoir totally changes the hydraulic head in the reservoir. This is a mutual effect of interrelations and interactions within the nexus system.

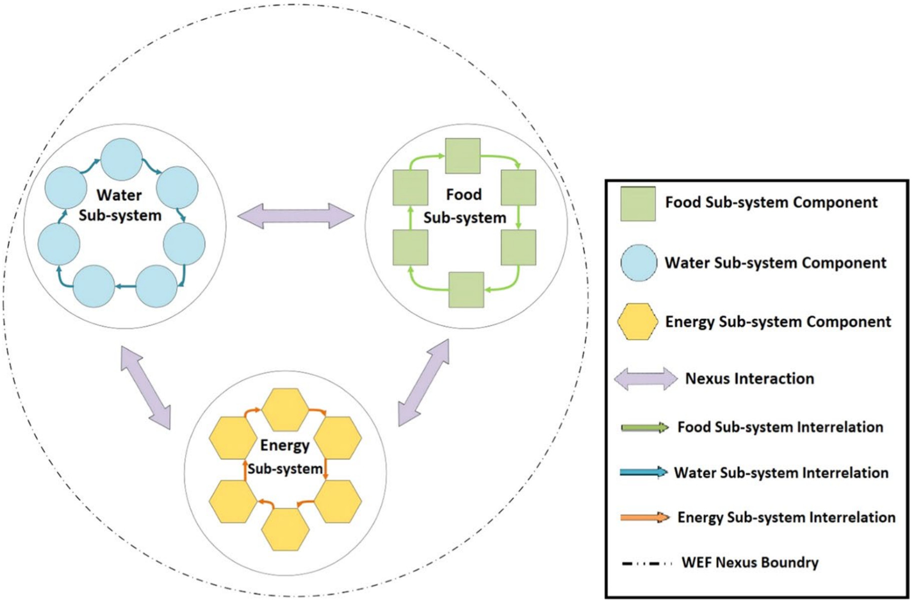

Fig. 1 The holistic WEF nexus boundary with interrelations and interactions

To model the WEF modules, the first step should be to collect the required data. The data in this paper are divided into two types: (i) non-simulated data, which consists of independent variables, independent parameters, and management variables, and (ii) simulated data which consists of interrelationships and interactions between variables. Separating nexus data will enable WEF nexus data to be seen better and implemented more efficiently.

The term independent parameter is used when describing parameters that are constant over time, such as the size of the watershed, length of the river, type of the soil, and type of cooling system in non-simulated data. An independent variable is one that exists outside the boundary of a system and changes with time. These variables can be changed with regard to the selected system boundary. For instance, precipitation, temperature, solar irradiance in both water and food, as well as energy simulator; Consequently, their alteration is not affected by the other subsystems. Furthermore, management variables are variables defined in the model by managers or the optimizer, and they can vary over time (For instance: the water subsystem's operation rules, the food subsystem's cultivation patterns, and the energy subsystem's production capacity).

Interrelations and interactions, which are belonged to the second category, were defined previously. Understanding these interrelationships is just as important as understanding the interactions between these three subsystems. By classifying data, the WEF nexus model will be able to understand and perceive these interrelationships and interactions. After discussing the interrelations in each subsystem, the interactions among them are extracted as IFs and THENs variables.

3.1 Water simulator

The water cycle is extremely complex and has a great deal of spatial and temporal variation. Due to the nonlinear interactions between these processes and the economic constraints of measuring components directly, the use of simulation models has greatly expanded over the years (UN, 2014). There are two main components of the water subsystem. The first one involves elements derived from the hydrology cycle, while the second involves components derived from man-made structures such as treatment plants and desalination plants. Figure 2 shows all components of the water simulator.

Figure 2 shows all the components of the water subsystem and their interrelations. Each of the arrows represents a distinct water subsystem interrelation. According to Fig. 2, the inputs of the water subsystem model are independent variables, independent parameters, and management variables, which are non-simulated data. As rain falls down and reaches the ground, some of it seeps into the soil, and once the soil becomes saturated, the rest of the rain becomes runoff. However, a certain amount of rainfall is lost in evapotranspiration,

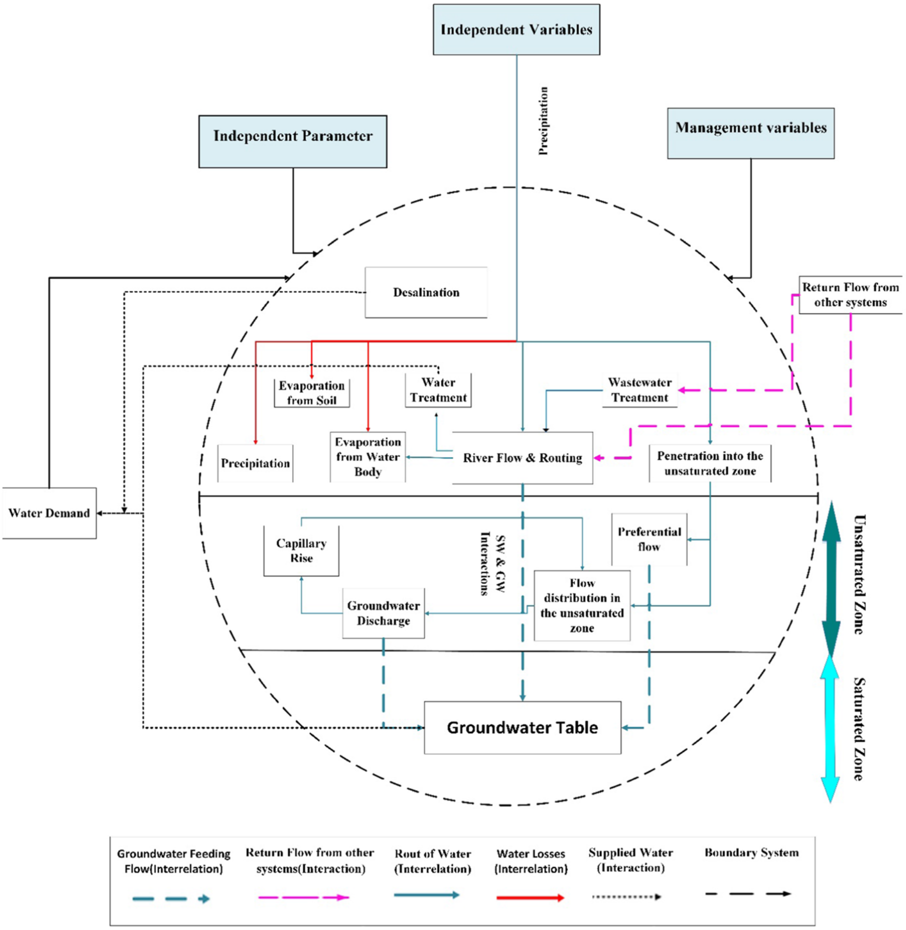

Fig. 2 The components of the water simulator and its interrelations

and it is attributed to the subsystem as well. These processes clearly show some interrelations in the water subsystem.

Surface and groundwater interrelations along the river bed are notable water subsystem interrelations. In fact, this interrelation is a major factor in recharging groundwater. Furthermore, groundwater is recharged by preferential flow and deep percolation. Besides hydrological processes occurring in the water cycle, man-made structures such as desalination, water, and wastewater treatment are included to supply water demand. There are many physical and empirical equations for simulating the water subsystem, though most of them aren't suitable for nexus due to the huge amount of data that's needed or that overlook some valuable relationships. With the nexus system, the attitude for water subsystem modeling can be totally different from the prior approach in which water subsystems were considered individually. For example, energy demand for water pumping is an obvious interaction between the water and energy subsystems. The energy subsystem needs to know two variables (groundwater hydraulic head and discharge) in order to calculate energy demand for pumping, so it is imperative that the water subsystem can calculate both variables, so they can interact with each other. In this context, it is necessary to choose appropriate equations for simulating the water subsystem while considering the nexus system requirements. Since surface water and groundwater are the fundamental elements of the water subsystem, their equations are explored in detail to extract simulated and non-simulated data.

3.1.1 Surface water simulation

The water level is an important variable for energy (Runoff) and food subsystems at different points in a basin, so distributed simulation of surface water is the best way to have a hydraulic head over time at each location (Molajou et al., 2021a, 2021b; Nourani et al., 2019). Saint–Venant's equation is a hydraulic method to route river flow. In this equation, continuity and momentum are involved, and there are three methods to determine river flow, which are the kinematic wave, diffusion wave, and dynamic wave. A number of studies have demonstrated that the kinematic wave method has acceptable performance, so it is discussed below. The equation which is needed to be solved is mentioned as Eq. 1 (Chow et al., 1998; Soentoro, 1991; Sturm & Tuzson, 2001):

$$\frac{\partial x}{\partial t} + \frac{dQ}{dA} = C_k \tag{1}$$

where C_k is the velocity of the kinematic wave, Q is river flow, A is a cross-section, x is related to place, and t is related to time. The A which was presented in Eq. 1, is an independent parameter, and Q is an interaction that affects another subsystem and takes an impression from other subsystems.

3.1.2 Groundwater simulation

The interrelation of surface water and groundwater has been observed numerically in many studies, so it's necessary to calculate groundwater head over time and spatial scale to quantify this interrelation (Afshar et al., 2021; Hatch et al., 2006; Song et al., 2020; Sophocleous, 2002). Boussinesq's equation has been selected as a proper equation to simulate groundwater here. For the solution of three-dimensional unsteady groundwater flow heterogeneously for a confined or unconfined aquifer, the partial differential equation (Bartlett & Porporato, 2018) is as follows:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \tag{2}$$

Here K_{xx}, K_{yy}, and K_{zz} are hydraulic conductivity, h groundwater's hydraulic head, W aquifer penetration rate (positive) and aquifer withdrawal rate (negative), S_s specific storage of porous space. This equation can be simplified. In other words, the groundwater flow velocity is low (meter per year); therefore, temporal changes can be neglected (Todd & Mays, 2004):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=0 \tag{3}$$

where W is a management variable that can be changed by the manager, and h, is the interaction that affects other subsystems and is influenced by other subsystems.

After identifying non-simulated and simulated data in surface water and groundwater, the remaining independent parameters, independent variables, and management variables can be determined by evaluating the other equations. It is important to note that depending on the equation selected for each subsystem, some variables and parameters will be altered. However, the main purpose of this paper is to demonstrate how we can recognize different effective variables on the WEF nexus. Table 1 shows the various data for the water subsystem.

3.2 Food simulator

The term food subsystem is frequently used in discussions related to socioeconomic development, health, nutrition, food, and agriculture. A food subsystem consists of all infrastructure and processes involved in providing food to people, such as cultivating, protecting, processing, packaging, harvesting, transporting, marketing, consuming, and disposing

Table 1 Water subsystem data in the context of the WEF nexus system

Independent parameters	Independent variables	Management variables
Watershed area	Precipitation	Surface water allocation
Length of river	Temperature	Groundwater allocation
Manning coefficient	Wind speed	Operation rule
Soil hydraulic conductivity	Initial soil moisture	Land management
Land use	Initial river flow	Agricultural machinery type
Dam location	Measured discharge in hydrometric stations	Irrigation method
Return flow location		Irrigation management (depth and time)
Return flow quantity		Production capacity of non-agri products
River flow hydraulic head in the base year		
Groundwater hydraulic head in the base year		
Groundwater abstraction		
Surface water withdrawal		

of food and food-related items (Pouladi et al., 2019, 2020). Additionally, it contains the required inputs and outputs generated by the above steps. A portion of the food subsystem is influenced by the economic, social, and environmental contexts, as well as political influences. Furthermore, it requires human resources, which can provide labor, education, and research (Ericksen, 2008; Maxwell & Slater, 2003; Singh & Tayal, 2021; von Braun et al., 2021; Wilkins & Eames-Sheavly, 2011).

The food subsystem is divided into two categories: agricultural and non-agricultural. The most important source of nutrition for humans and livestock is agriculture, so agricultural lands are water and energy-intensive. In this regard, food subsystems require a dynamic model that can simulate crop growth so that its interrelations with itself and its interactions between the energy subsystem and water subsystem can also be considered. Crop simulation models are defined as a model that can take into consideration of leaves, stems, and roots growing stages. The simulation models calculate growth, development, and efficiency by solving equations that are governed by soil, leaf, climate, management decisions, including irrigation types, agricultural inputs, and so forth (Dourado-Neto et al., 1998; Jones et al., 2017). Figure 3 illustrates the process of agricultural crop production.

Crop simulation models require four main data sets, which include independent parameters and variables, management variables, and dependent variables (IFs and THENs). Based on these data and dependent variables from the other two subsystems, the tillage, planting, growing, and harvesting processes are simulated in the crop's simulation model. Food simulation models will have a number of interrelations, such as fertilizer utilization for cultivation during the simulation process. The growing stage is the most important section of the crop simulation model. Crop yield is determined by means of the Doorenbos

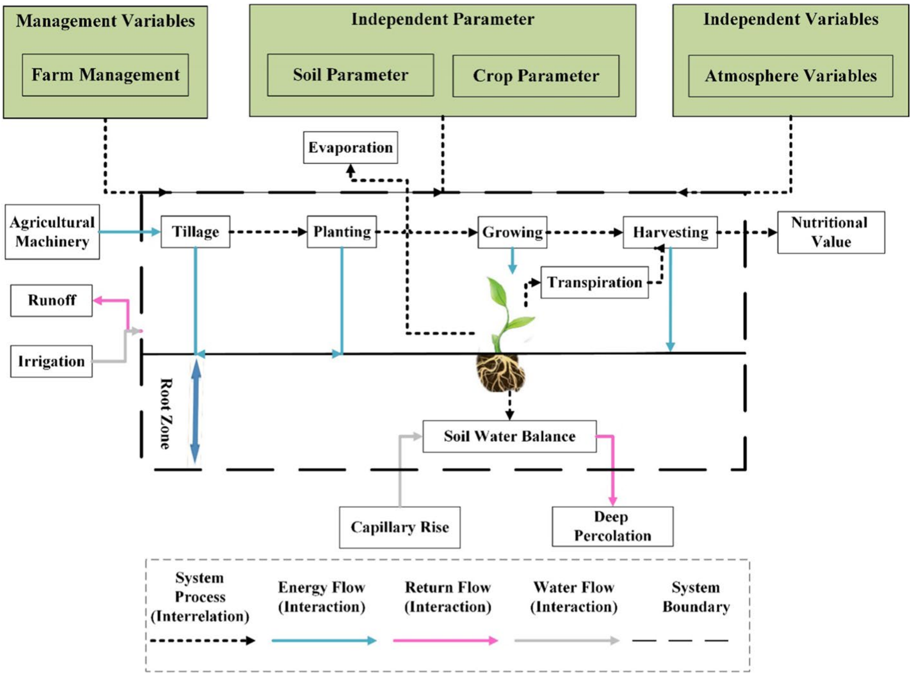

Fig. 3 The components of the food simulator and its interrelations

and Kassam equation, which has been derived from FAO-33 (Doorenbos & Kassam, 1979):

$$\left(\frac{Y_{x-}Y_a}{Y_x}\right) = K_y\left(\frac{ET_{x-}ET_a}{ET_x}\right) \tag{4}$$

where Y_x is maximum theoretical yield (corresponding to ETx), Ya actual crop evapotranspiration (corresponding to ETa), ETx potential evapotranspiration, ETa actual evapotranspiration, and Ky is the yield response factor to water stress. It's important to mention $Y_{x\ \mathrm{and}}$ Ky are emanated from FAO-33 and FAO-56. The actual evapotranspiration (Et_a) is calculated based on water balance in the root zone, and crop transpiration and the potential evapotranspiration are calculated based on Eq. 5 (Allen et al., 1998):

$$ET_x = K_c ET_0 \tag{5}$$

where ET_0 is the reference evapotranspiration of crop, which is calculated via the FAO Penman–Monteith method (Allen et al., 1998), and K_c is the crop coefficient. According to the equations mentioned above, crop yield is proportional to evapotranspiration. The amount of evapotranspiration by crops varies with crop types, irrigation rates, groundwater hydraulic heads, and atmospheric conditions.

In addition to agricultural byproducts, non-agricultural byproducts are included in the food subsystem. The agricultural sector is very closely interrelated with this section; for example, crops are required to supply feed to livestock. As a result, livestock production is interrelated with different irrigation and field management methods as well as evapotranspiration, crop growth, and soil moisture equations. Table 2 lists the independent parameters, independent variables, and management variables of the food simulator.

3.3 Energy simulator

Almost all economic activities are dependent on energy, and reliable access to energy is vital to national security in many countries. Thus, the production and consumption of energy carriers are one of the key issues around the world. It's crucial to model the energy subsystem because of the complex relationships between its components and because of the complexity that exists inside it. Figure 4 shows the components of the energy subsystem.

Table 2 Food subsystem data in the context of the WEF nexus system

Independent parameters	Independent variables	Management variables
Temperature (Crop parameter)	Rainfall	Cultivation area
Salinity	Temperature	Planting and harvesting date
Water stress coefficient	Wind speed	Agricultural inputs
Length of the crop growth cycle	Humidity	Land management
Saturated hydraulic conductivity	Vapor pressure	Agricultural machinery type
Soil water content at field capacity	Carbon dioxide concentration	Irrigation method (drip, sprinkler, etc.)
Permanent wilting point		Irrigation management (depth and time)
Saturation		Production capacity of non-agri products

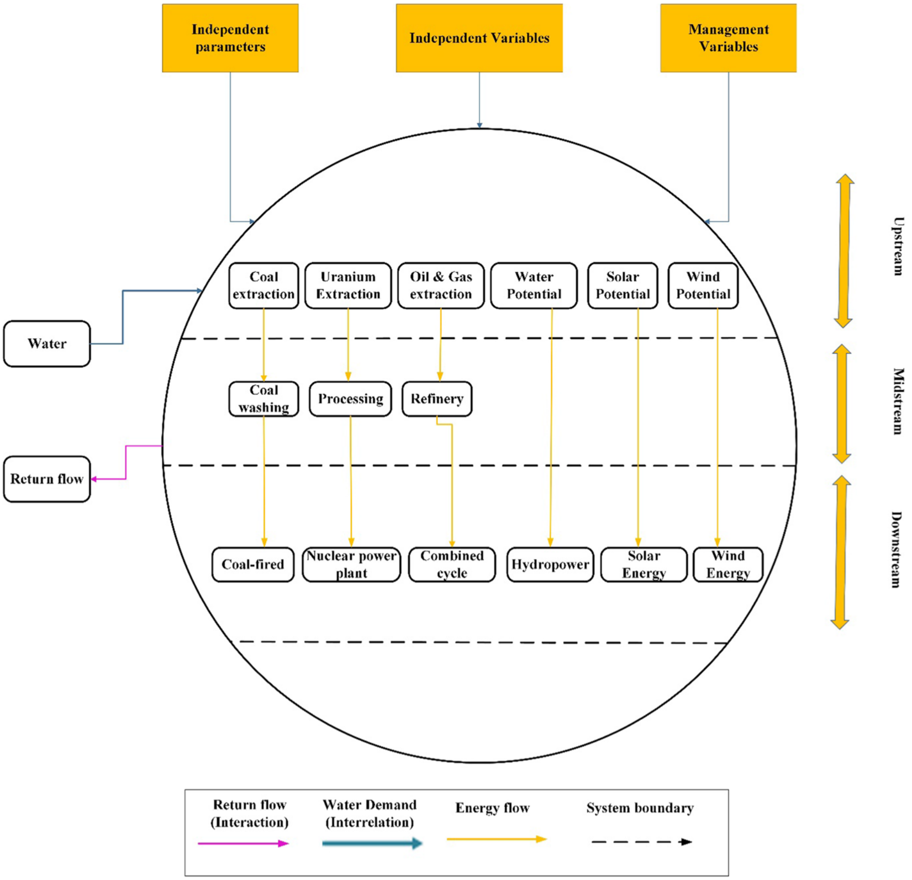

Fig. 4 The components of the energy simulator and its interrelations

The process of energy flow, as well as some inputs and outputs, is illustrated in Fig. 4. The energy subsystem has inputs such as independent parameters, independent variables, and management variables that are categorized in the following. A further division of the energy subsystem can be found below in the sections devoted to the supply side of the energy subsystem and the demand side.

3.3.1 Energy supply-side

The most important part of the energy subsystem is its supply-side, which can be divided into three sections: upstream, middle stream, and downstream. The upstream flow is related to the extraction of fossil fuels, such as crude oil, gas, and so forth. It is significant that water, wind, and the sun are neither extracted nor processed like fossil fuels but are considered either for upstream or middle streamflow. In the following step, the middle stream is allocated for processing. To put it another way, fossil fuel should be processed so that it can be used in power plants, industrial processes, and other applications. Lastly, downstream refers to thermal power plants, transmission, and distribution.

3.3.2 Energy demand-side

The demand side of the energy subsystem is divided into two sections: intersystem demand and intra-system demand**.** The intersystem demand is the demand for the two other subsystems, i.e., water and food, and the intra-system demand is dependent on internal demand such as transportation, domestic, commercial, etc.

In regard to the definition of interrelation and interaction previously defined, the energy carriers required for the extraction, processing, and production of energy carriers can be viewed as an illustration of interrelation. To produce crude oil offshore, for example, energy must be allocated to the extraction process. In addition, the water which is used in the energy subsystem in order to produce, extract and process energy carriers are the obvious interaction that exists inside of the subsystem. Thermal power plants, for example, need a large amount of water to cool their systems, and after cooling power plants, some of the water is returned to the water bodies. These are clear interactions (IFs and THENs) that exist between water and energy subsystems. The energy subsystem data needed by the WEF nexus system are given in Table 3.

3.4 Holistic WEF nexus simulator framework

The WEF nexus simulator can be implemented at any scale by considering simulated data (IFs and THENs) for WEF nexus interactions. In addition to selecting different spatial scales altering nexus components and causing differences in system boundaries, it is crucial to mention that selecting different spatial scales can produce different nexus components over time as well. As a result, all system boundaries will overlap as the spatial scale is widened. Despite restricting the spatial scale to the smaller boundaries such as a watershed, the system boundaries of WEF subsystems are different in such a way that the boundary of the energy subsystem is the biggest, while the boundary of the water subsystem is the smallest. In more detail, on a national scale, all WEF subsystems include their own components due to large spatial boundaries. While in the watershed, the production of energy is not restricted to a single watershed at the scale of a watershed or a specific energy subsystem. It can typically be produced in another area and imported into the watershed. The result is that it cannot be possible to examine all the interrelations in the energy subsystem at the watershed scale unless it is possible to

Table 3 Energy subsystem data in the context of the WEF nexus system

Independent parameters	Independent variables	Management variables
Power plant efficiency	Sunny days	Fossil fuels production capacity
Processing unit efficiency	solar irradiance	Power plant unit's production capacity
cooling system type	Wind speed	Processing unit's production capacity
Maximum capacity of fossil fuels extraction	wind direction	Land management
Minimum capacity of fossil fuels extraction		
Maximum capacity of power plants and refineries		
Minimum capacity of power plants and refineries		

consider bigger spatial scales such that they include many energy components. On the other hand, basic water resources like surface water and groundwater are located in the watershed. Consequently, these differences should be taken into account when defining system boundaries at a small spatial scale.

Here, it has been attempted to examine all the interactions between WEF subsystems. Figure 5 shows the IFs and THENs for the WEF nexus simulator. The reason that interactions on the WEF nexus system are called IFs and THENs is based on the fact that the output of one subsystem is considered as an input for another subsystem. For example, deep percolation is an output of the food subsystem (THEN), which the water subsystem uses as input (IF). In this category, each of the simulation models has its stand-alone outputs (THENs), which are not used by other subsystems, and indeed they're called independent THENs. In the WEF nexus system, environmental water demand in the water subsystem supplied energy for non-nexus demands and non-agricultural byproducts are an example of independent outputs.

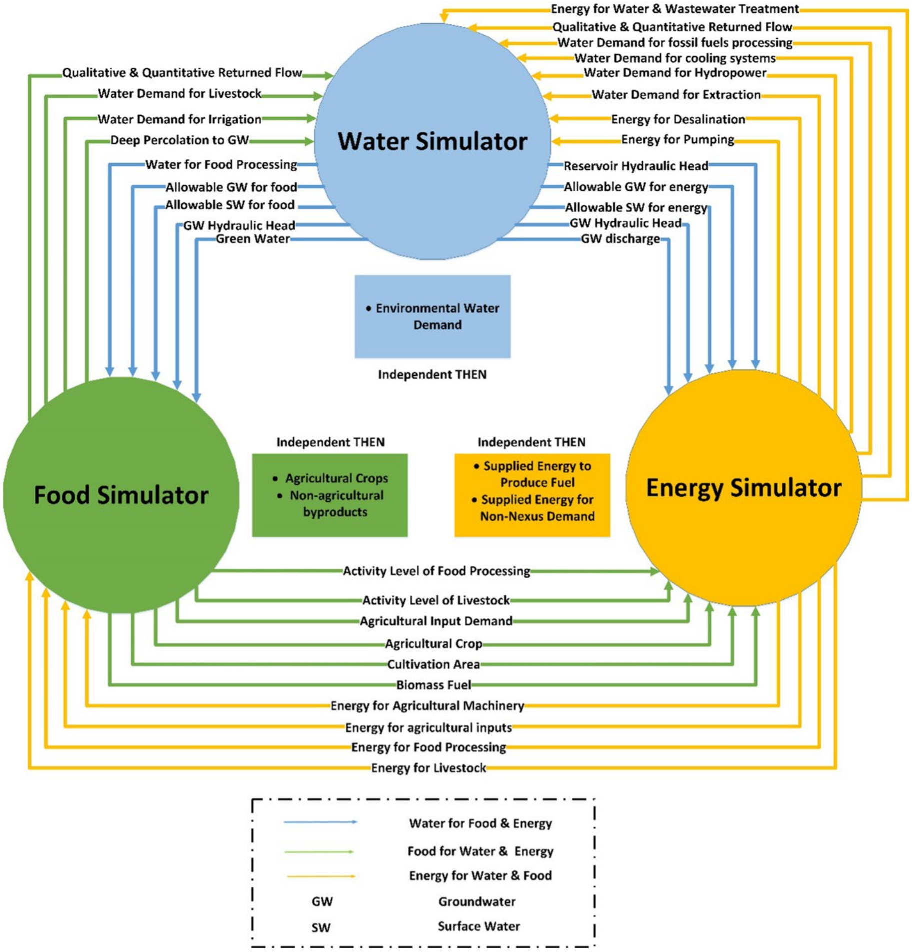

Fig. 5 The interactions between the WEF nexus system

IFs and THENs in the nexus concept are shown in Table 4. It would enable researchers to analyze WEF nexus interactions precisely through this categorization. It is essential in Fig. 5 that all IFs and THENs are presented, so they can be revised based on the spatial scale of the case studies.

According to Table 4, all interactions between three resources are categorized. As an example, the first interaction between food and energy is described by the activity level of food processing, which determines the energy requirement for machinery in different phases of processing, such as the cultivation and harvesting phases. On the other hand, using machinery has a consistent energy demand per acre. Biomass fuels are another interaction between the two subsystems, and biomass is counted as an energy resource. In order to clarify, producing different amounts of biomass would produce diverse amounts of energy. However, the expected amount of energy produced from biomass depends entirely on the food subsystem management strategy and the amount of biomass produced.

3.5 Case study

Qatar county is considered a case study to demonstrate how the proposed IFs and THENs work. Qatar is located in the Middle East and in the Southern part of the Persian Gulf. This country is known for its three main characteristics: its scarcity of water, its abundance of natural gas, and its very dry climate, which leads to importing more than 90% of its food. Over the past few years, Qatar's top executives and decision-makers have been working on a comprehensive food security plan based on security concerns. Qatar was chosen for the study because the WEF Nexus Tool 2.0, one of the oldest and most widely known WEF nexus models, was developed in Qatar.

4 Result and discussion

The following steps must be taken before identifying IFs and THENs variables. Below is a list of all steps that need to be taken:

(1) Determine subsystems included in the WEF nexus system: The main aim of this step is subdividing nexus system to subsystems to understand how many elements are involving in nexus (Water-Energy; Water-Food; Energy-Food; Water-Energy-Food). The WEF nexus system in Qatar includes all three resources with some specific components.

(2) Define each subsystem boundary and components: This step is indispensable to determine which relations should take into account as interactions or interrelations. Based on a previous study about Qatar, it appears that it has some WEF subsystem elements. A permanent surface water source is not available in the water subsystem, and groundwater is the primary source for irrigation. Due to water scarcity, low water quality, unsuitable climatic conditions, unfertile soils, and poor water management, agricultural development is limited in the food subsystem. Owing to these limitations, more than 90% of the food it consumes is imported. According to FAO statistics, only 30% of cultivable land was used by 1995, and in terms of the energy subsystem, there is a lot of natural gas and oil, which is the main source.

(3) Select spatiotemporal scale for simulation: In general, choosing the scales affect the entire simulation because it specifies the importance, degree, and priorities of the

Table 4 IFs and THENs of WEF nexus concept

THEN IF	Water	Energy	Food
Water	Environmental water demand	Reservoir hydraulic head Allowable groundwater for energy Allowable surface water for energy Groundwater hydraulic head Groundwater discharge	Water for food processing Allowable groundwater for food Allowable surface water for food Groundwater hydraulic head Green water
Energy	Energy for water & wastewater treatment Qualitative & quantitative returned flow Water demand for fossil fuels processing Water demand for cooling systems Water demand for hydropower Water demand for extraction Energy for desalination Energy for pumping	Supplied energy to produce fuel Supplied energy for non-nexus demand	Energy for agricultural machinery Energy for agricultural inputs (Seeds and Fertilizer, etc.) Energy for food processing Energy for livestock
Food	Qualitative & quantitative Returned flow Water demand for livestock Water demand for irrigation Deep percolation to groundwater	Activity level of food processing Activity level of livestock Agricultural input demand Agricultural crop Cultivation area Biomass fuel	Agricultural crops Non-agricultural byproducts

problem. As a result, steps two and three are closely related. The study considered annual and national scales as spatiotemporal scales.

(4) Select the best method to simulate each component on the subsystems: This step is critical because it affects the IFs and THENs variables in the simulation. Different approaches are used to model the various subsystem components according to the type of analysis required and the accuracy requisite. In this paper, as mentioned earlier, Eq. 2 and Eq. 4 are considered to simulate groundwater and crop growth, respectively. In the energy subsystem simulations, interactions were not considered, and the Balance equation will be used to recognize interrelations.

(5) Extraction of interrelations on each subsystem with reference to previous steps: Based on the previous step and the equation used, the interrelation of each subsystem is determined. In addition to determining all interrelations in each subsystem, it will also affect the interactions between them. In other words, these interrelations and interactions have an effect on each other. For instance, the relation between unsaturated zone and groundwater, which is mentioned in Table 5, is interrelation in water subsystem, which can have an effect on the interaction between water subsystem (Groundwater level) and energy subsystem (Energy demand for groundwater pumping).

(6) Extracting interactions (IFs and THENs) variables based on previous steps: The IFs and THENs variables can be determined by looking at the components of each subsystem and their mutual effects. Figure 5 is extremely helpful in facilitating this step. In Tables 5 and 6, all the interrelations and interactions of Qatar's country are shown.

Table 5 Interrelations between WEF subsystems in Qatar country

	Water	Energy	Food
Water	Flow distribution in the unsaturated zone Capillary rise Groundwater storage		
Energy		Energy carriers to extract, process, and produce energy	
Food			Soil fertility Planting time Growing Harvesting time Transpiration Soil water balance Deep percolation Capillary rise

Table 6 IFs and THENs of WEF nexus concept on Qatar country

IF THEN	Water	Energy	Food
Water	Environmental water demand	Allowable groundwater for energy Groundwater discharge	Water for food processing Allowable groundwater for food Groundwater hydraulic head Green water
Energy	Energy for water & wastewater treatment Qualitative & quantitative returned flow Water demand for fossil fuels processing Water demand for fossil fuels processing Water demand for cooling systems Water demand for extraction Energy for pumping energy for desalination	Supplied energy to produce fuel	Energy for agricultural machinery Energy for agricultural inputs Energy for food processing Energy for fertilizer Energy for transport
Food	Qualitative & quantitative returned flow Water demand for irrigation Deep percolation to groundwater	Activity level of food processing Agricultural demand Agricultural crop Cultivation area	Agricultural crops

In the water subsystem, flow distribution in the unsaturated zone, capillary rise, and groundwater storage are considered as interrelations. In Table 5, the interrelations of each subsystem are shown.

As shown in Table 5, energy is needed to extract and process energy and forms a kind of interrelation in the energy subsystem. It means these energies are used in the system boundary by the energy subsystem. There is an interrelation between tillage, planting, growing, and harvesting in the food-food box. These processes have an effect on each other such that tillage determines the amount of planting and how much planting is involved in the growing and harvesting phases. By changing each process, it is expected that the next one will also change. Transpiration, soil water balance, deep percolation, and capillary rise, which are all mentioned in Table 5, are other interrelations components of the food web. Due to their effect on other quantities, they are considered interrelations.

Following all steps causes nexus data to be classified into simulated and non-simulated categories, as stated in the case study section. Here, the most important data are interactions or IFs and THENs variables. Table 6 shows the IFs and THENs variables in Qatar.

Using the proposed framework, Table 6 categorizes all interactions between WEF in Qatar. According to a previous study on the nexus specifically in Qatar, the interactions were tillage, harvest, fertilizer, and transport between energy and food subsystems, and also pumping, desalination, water, and wastewater treatment between water and energy (Daher & Mohtar, 2015). Due to the ambiguity of the nexus concept, the IFs and THENs variables highlighted in Table 6 were not included in the previous study about this case study. As a result, the IFs and THENs framework was used. Using this framework, it is obvious that more interactions will be distinguished, which will improve the accuracy of implementing nexus.

5 Conclusion

Identifying all the interrelations and interactions between WEF resources is essential in understanding the WEF nexus concept. A comprehensive nexus simulator model needs to be developed to investigate all interrelationships and interactions. A conceptual framework for a holistic nexus simulator was presented as the first step. Then, to facilitate the application of the nexus concept, required data were categorized into non-simulated and simulated data to identify all interactions and interrelations.

In this paper, the interrelations of each subsystem in the WEF nexus were investigated, and the required data for WEF subsystems were represented. Then, the interactions (IFs and THENs) among the three subsystems were explored, and the needed data were categorized. These IFs and THENs help us to understand and resolve the complexity of the WEF nexus concept, thus allowing us to simplify the WEF nexus concept with these classifications. In other words, IFs and THENs variables show the relationship between three subsystems. It would be understandable by deleting one IFs variable on a specific subsystem which of the following THENs variable will be eliminated from another subsystem. Therefore, interactions will be easily determined despite previous efforts on nexus, which didn't provide details on how to initiate and discover interactions. On the other hand, the classification method presented here would make it possible to deal with the nexus interactions within holistic nexus simulators. It means each relation and its impact on other subsystems can be tracked.

Declarations

Conflict of interest statement The authors declare that they have no conflict of interest.

Data availability The authors declare that the data are not available and can be presented upon the requested of the readers.

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