The Conceptual Socio-Hydrological Based Framework For Water, Energy and Food Nexus

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The Conceptual Socio-Hydrological Based Framework for Water, Energy and Food Nexus

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Abstract

The current study introduces a conceptual socio-hydrological based framework for water-energy-food (WEF) nexus. The proposed conceptual framework aims to investigate how farmers' dynamic agricultural activities under different socio-economic conditions affect the WEF systems. The WEF nexus model has been integrated with an Agent-Based Model, reflecting the farmers' agricultural activities. Furthermore, the agent-based model benefits from Association Rule Mining to define farmer agents' agricultural decision-making in various conditions. The processes within the WEF nexus are simultaneously physical, socio-economic, ecological, and political. Indeed, there are interrelated interactions among the mentioned processes in ways that have not yet properly delineated, mapped, or even perceived. Thus, for obtaining sustainable outcomes, the current study attempts to investigate trade-offs among natural resources and social systems in the WEF nexus approach. The proposed framework may provide more in-depth future insights for policy-makers through capturing bidirectional feedbacks among farmers and WEF systems. Furthermore, the proposed socio-hydrological WEF nexus framework can be adapted and applied to various societies and environments to provide more in-depth future insights for policy-makers through capturing bidirectional feedbacks among farmers and WEF systems.

Keywords: Water-energy-food Nexus; Socio-Hydrology; Agent-Based Modeling; Data Mining; Association Rule; Urmia Lake

1. Introduction

Food, energy, and water are inseparably interrelated resources that are vital for subsistence, sustainability, and development of every society (Li et al., 2019a; Shang et al., 2018). Agricultural activities play the leading role in providing food security; however, by being the largest consumer of freshwater resources, it also affects energy security and hydrological systems (Tian et al., 2018). Food production consumes about 90% of the freshwater resources, and approximately 30% of global energy use for production and related supply chains (Zhang and Vesselinov, 2017; Karnib, 2018). Nevertheless, due to world population growth and economic developments, new environmental challenges have also emerged, which have the potential to aggravate the insufficiency of water and energy resources. It has been estimated that by 2030, demand for water, energy, and food will be increasing by 30%, 40%, and 50%, respectively (Yang et al., 2016; White et al., 2018; Li et al., 2019a, 2019b). Therefore, efficient and sustainable management of limited energy and water resources is indispensable to address the food demand of growing populations (Taniguchi et al., 2017; Li et al., 2019a; Molajou et al., 2021).

In most parts of the world, national strategies on the governance of one system are frequently established independently from the other two systems; subsequently, the interlinkages among the three systems may not be appropriately considered. Thus, implementing management policies in one division of food-water-energy often leads to conflicting strategies, repercussion impacts on other systems, and amplified competition for the same resources (Daher and Mohtar, 2015; Dang and Konar, 2018). At this point, as a way to reach sustainable development goals, the water-energy-food (WEF) nexus approach has been brought into the light at the Bonn conference of 2011 (Hoff, 2011; Scott et al., 2015). While highlighting the interdependencies and interlinkages among resources, the nexus approach offers insights on how to execute integrated management strategies for environmental resources without neglecting their spillover impacts on other systems and their implications for the extent of scarcity (World Economic Forum, 2011; Endo et al., 2017; United Nations, 2016; Ai-Saidi and Elagib, 2017; Kurian, 2017). In recent years, the conducted works in WEF nexus have been mainly focused on understanding the correspondences and synergies of food, water, and energy (Wolfe et al., 2016, Foran, 2015; Cai et al., 2018), creating an analytical framework to strengthen integrated management outcomes for improving energy, water, and food security (Scott et al., 2016; De Vito et al., 2017; White et al., 2018), and the political aspects of WEF divisions to reach nexus goals (Biba, 2016). However, in the anthropogenic era, where numerous instances of unsuccessful attempts to tackle environmental challenges have resulted in unanticipated consequences, there are limited studies on the WEF nexus investigating the dynamic impacts of anthropogenic systems on the future trajectories of nexus (de Grenade et al., 2016; Ramaswami et al., 2017; Spiegelberg et al., 2017; Newell et al., 2019; Li et al., 2019a, 2019b).

The increasing interventions of human activities in environmental processes have ended up in significant alterations of natural resources and failure in various environmental management strategies (Dang and Konar, 2018; Kuil et al., 2019; Moshir Panahi et al., 2020). Regarding the processes within the WEF nexus, which are simultaneously physical, socio-economic, ecological, and political, indeed, there are interrelated interactions among the mentioned processes in ways that have not yet delineated, mapped, or even perceived (Howells et al., 2013). In this regard, nexus approaches require strong transdisciplinary and interdisciplinary joint efforts (Newell et al., 2019). Thus, for obtaining sustainable outcomes, it is necessary to investigate socio-ecological resilience, tradeoffs among physical and social systems, anthropogenic impacts on the condition of natural resources, social externalities of natural resources governance, the influences of nexus on human livelihoods, and vice versa in WEF nexus approaches (Scott et al., 2015; Biggs et al., 2015; Taniguchi et al., 2017, Bakarji et al., 2017; Di Baldassarre et al., 2019).

This research aims to deliver a WEF nexus framework for investigating how farmers' dynamic decisions and activities can shape the co-evolutionary trajectories of humans and WEF systems. As a novel strategy, this research benefits from the integration of a socio-hydrological model with a WEF nexus model to incorporate farmers' dynamic activities within nexus in a more detailed manner. One of the significant points of the proposed socio-hydrological WEF nexus framework is its ability to be adapted and exercised for various societies and environments. Thus, the proposed framework may open a window to have more precise future insights for policy-makers through capturing bidirectional feedbacks among farmers and WEF systems. For assessing the efficiency of the proposed integrated framework, it has been applied to the Zarrineh-Rud River Basin in Iran, which is experiencing serious environmental challenges due to conflicting environmental needs and agricultural activities.

2. Study area

After the desiccation of the Aral Sea because of human-oriented developments, it has been argued that the Urmia Lake (Iran), one of the largest Lakes in the world, might experience the same fate (AghaKouchak et al., 2015). In recent decades, due to the significant growth of agricultural developments, the area of Urmia Lake has catastrophically shrunk without any restoration. Alongside almost 90% drop in the Urmia Lake level, the increase in farm areas has nearly reached its maximum capacity, which has caused severe environmental stresses (ULRP, 2017; Khazaei et al., 2019). Several studies suggested due to the anthropogenic nature of this critical environmental challenge, there is a necessity to have a practical framework for managing natural resources (Ashraf et al., 2019; Ghale et al., 2018). Thus, the proposed framework has been applied on Zarrineh-Rud River Basin, supplying the main surface water inflow (more than 49%) to the Urmia Lake (Henareh Khalyani et al., 2014).

The growing season in the Zarrineh-Rud River Basin mainly begins in the mid-spring and lasts until the mid-autumn. During the growing season, irrigation water demands are extracted by farmers from both surface water and groundwater resources. It should be noted that the total area of agricultural farmlands in the study area is about 74 318 ha (Emami and Koch, 2018). In the given region, the crops being cultivated in almost 92% of the farms include wheat, barley, corn, alfalfa, tomato, onion, and sugar beet.

3. Socio-Hydrological WEF Nexus Framework

In many countries, agricultural activities have a significant role in enhancing the economy, and providing food security of the societies. Therefore, one way to improve the economic condition is through elevating agricultural productivity. As discussed earlier, studies on WEF nexus mainly explore the optimized strategies leading to the most beneficial outcomes for all food, water, and energy sectors. However, regardless of how dynamic farmers may behave, these entities mainly have been considered as statistical elements or boundary conditions (Dang and Konar, 2018; Di Baldassarre et al., 2019). WEF systems have significant direct and indirect dependence on the condition of water resources. Respectively, as dynamic activities of farmers relating to irrigation, land-use change, and crop choice may alter the condition of water resources, it can be inferred that farmers have the potential to affect the whole WEF nexus system as well (see Fig. 1).

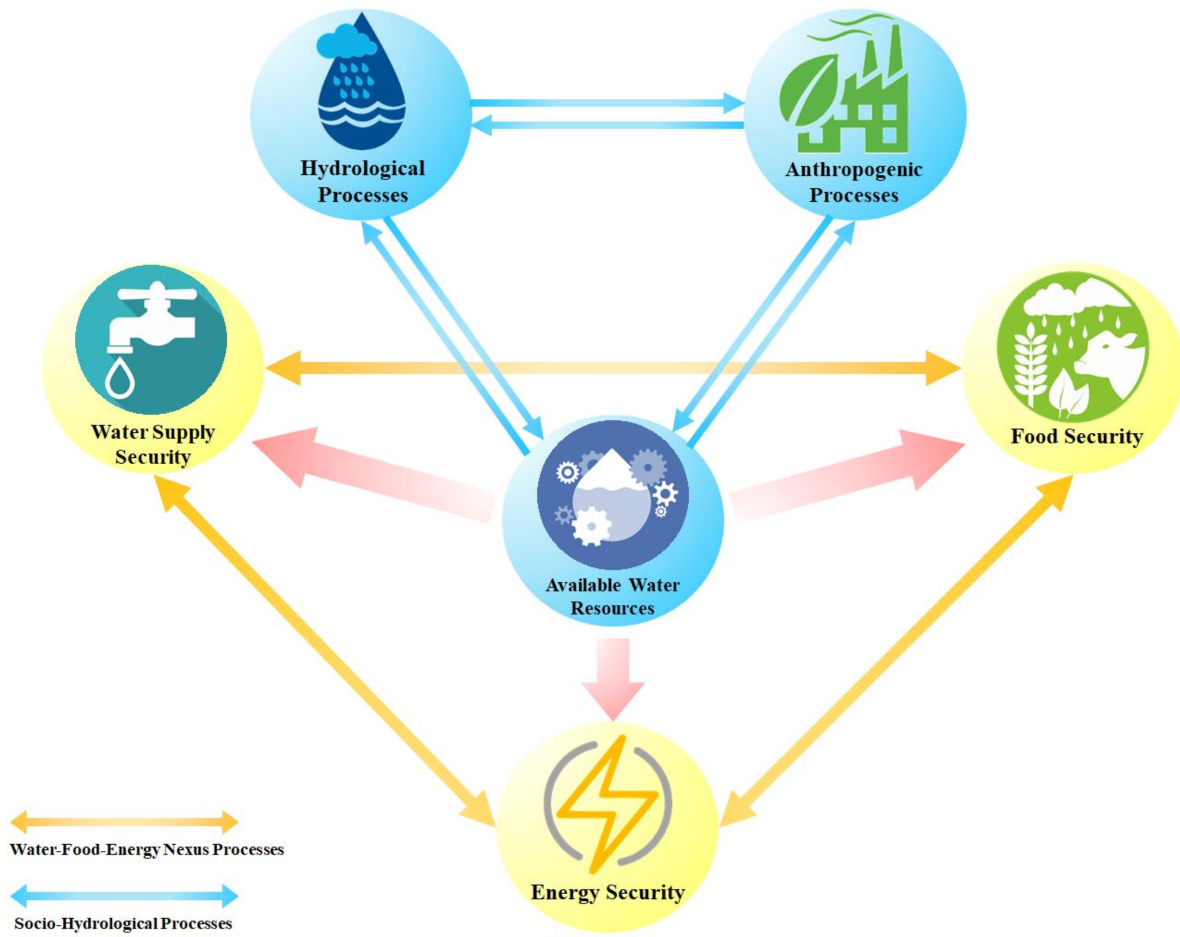

Fig. 1 The conceptual framework of socio-hydrological WEF nexus system

As presented in Fig. 1, the socio-hydrological loop has been jointed within the WEF nexus framework through available water resources. Socio-hydrological loops can contain a wide variety of anthropogenic processes that may cause severe drought in available water resources. Therefore, to capture anthropogenic dynamics, a hybrid socio-hydrological simulation model consisting of the Association Rule Mining (ARM) and Agent-Based Model (ABM) has been employed to inspect farmers' activities. ABM has been exercised to address the two-way feedbacks of farmers' agricultural activities and available water resources from the socio-hydrological viewpoint. In the ABM, agents are representing farmers who interact with surface water and groundwater resources for irrigation purposes. The impacts of farmers' agricultural activities may vary by the crop-type that they cultivate, and the choice of crop-type depends on different factors such as financial condition, agricultural possessions, and social characteristics. Therefore, to have an accurate ABM, behavioral rules of the farmer agents have been extrapolated through ARM based on the analysis of farmers' social, financial and agricultural real-world properties. Afterward, the outcomes of the hybrid ABM and ARM affect the WEF nexus model, which have been created in System-Dynamics (SD) environment.

The WEF nexus SD model provides the environment for the ABM, which is in interaction with the farmer agents. For each of the WEF systems, there is a SD sub-model representing the condition of the given system and functions in tandem of other WEF sub-models. The proposed nexus simulation model consists of three sub-models affecting each other's performances.

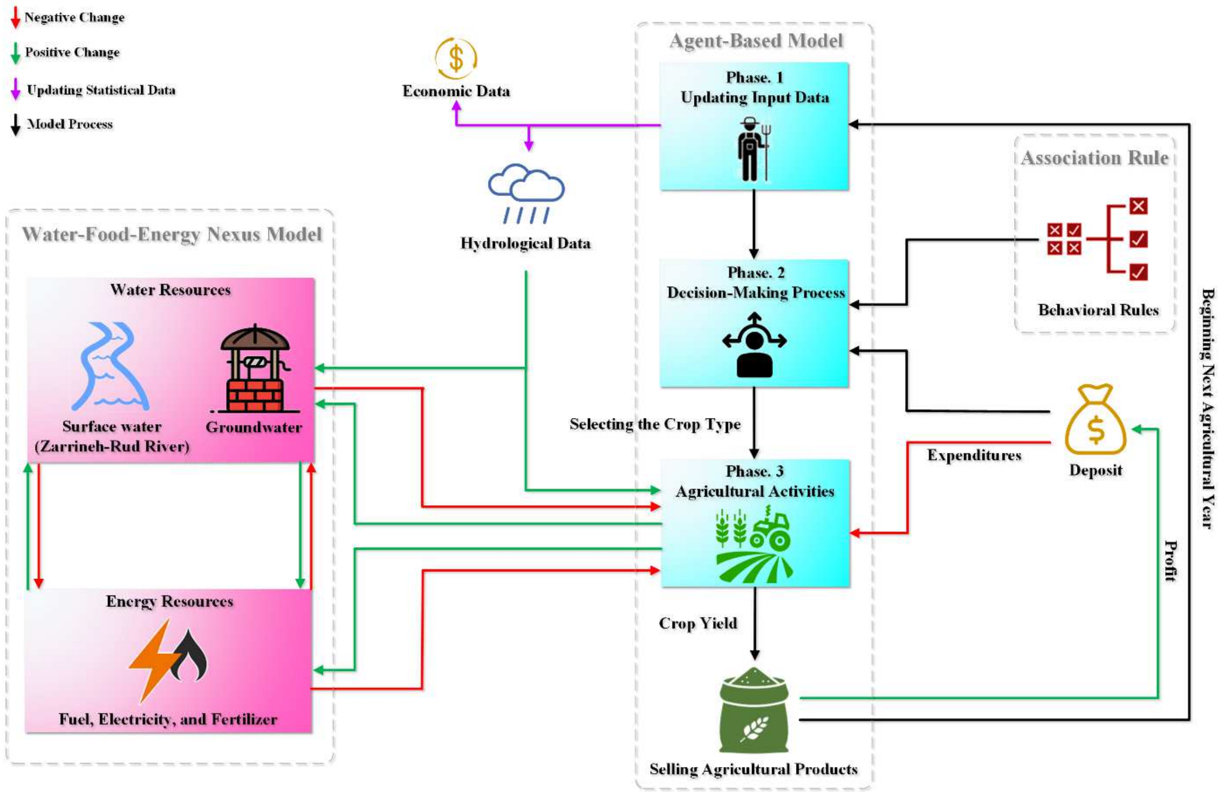

Fig. 2 The schematic overview of socio-hydrological WEF nexus simulation model

Fig. 2 demonstrates the schematic overview of the model, highlighting the connections among decision-making, human activities, and WEF systems. In the following sections, the employed sub-models have been explained.

3.1 Association Rule Mining (ARM)

The ARM is a data mining method, which aims to extract causal structures, frequent patterns, associations, or noteworthy correlations between data sources. ARM measures the strength of the patterns to identify reliable rules from the given databases. An association rule of $E \Rightarrow F$ represents that it is very likely that F happens as a result of happening E in a transaction from the database.

In this regard, E is antecedent, and F is the consequent of the rule. The reliablity and dominance of a rule between all of discovered rules are defined by measures of support and confidence. The measure of support indicates the frequency of the transactions satisfying both considered antecedent and its consequent in the database (Eq. (1)). The measure of confidence represents the percentage of the transactions within the database including both E and F (Han et al., 2006; Nourani and Molajou, 2017; Nourani et al., 2017).

$$S(E \rightarrow F) = P(E \cup F) \tag{1}$$

$$C(E \rightarrow F) = P(E \mid F) = P(E \cup F)/P(E) \tag{2}$$

Where C is confidence and S is support, and in which E, $F \subseteq Y$, where Y represents a dataset of transactions.

In this study, to have more accurate ABM, which can mimic farmers' decision-making based on social, environmental, and economic conditions, the behavioural rules of the agents have been determined through ARM. According to the previous studies and consulting with the specialists from the Urmia Lake Restoration Program (ULRP), the social data referring to the main non-psychological attributes of the farmers with the most universality have been gathered through interviews, filled questionnaires, and social background studies (Jepsen et al., 2006; Gocsik, 2014; Yekom, 2016a, 2016b). The mentioned questionnaire is shown in Table 1.

Table 1. The social properties of the farmers, which have significant impacts on their agricultural activities

Agricultural knowledge	Age	Financial satisfaction	Ownership of the farm	Size of the farmland	Location of the farmland alongside the main river channel
Poor	Young	Poor	Rented	Small	Upstream
Medium	Adult	Medium	Owned	Medium	Downstream
Good	Old	Good		Large	Near diversion dam

Having well in the farm	Selling contract	Household labor working on the farm	Availability of agricultural machinery	Livestock farming	Education level	Type of the nearby water resources
Yes	Yes	Yes	Yes	Yes	Illiterate	The lake
No	No	No	No	No	Primary	The main irrigation canal
					High school	The nearest dam
					University	The main river

Using the results of the filled questionnaries, the ARM was utilized to extrapolate the pattern of the essential attributes making farmers decide to plant a specific crop type or not. For this study, the analysis of social data through ARM has been conducted in the Weka (Waikato Environment for Knowledge Analysis) software.

3.2 Agent-Based Model (ABM)

As shown in Fig. 2, the ABM processes consist of three main phases. In the first phase, the model receives historical hydrological and economic data as inputs. The statistical hydrological data include precipitation, mountain streams, and the average amount of industrial and urban water demand. And, the economic data contains the production costs and selling prices of the agricultural products. The mentioned input data may be considered as the boundary conditions for the ABM environment; therefore, they will be updated beginning each agricultural year, according to the gathered data.

In the 2nd phase, the agents initiate the decision-making processes for the upcoming agricultural year. For this purpose, to have agents representing farmers of the Zarrineh River Basin, the agents have been characterized in the model with various social and agricultural characteristics based on the parameters of Table 1. Therefore, each group of agents has diverse characteristics and conditions that affect their decision-making processes.

Based on the interviews with the farmers, the financial condition is among the top factors affecting farmers' agricultural decisions. Therefore, the agents assess their economic condition to choose the crop type that they want to cultivate next year. In this regard, agents use Eq.3 to determine the amount of money (*Deposit*) they expect to have for each of the upcoming twelve months minus the average agricultural costs for a year ($Cost_{avg}$) before gaining the next profit from selling agricultural products. Then, the agents compare their financial condition (F_c) with the poverty threshold of the year (P_{Th}).

$$F_c = \left(\frac{Deposit - \ Cost_{avg}}{12}\right) \tag{3}$$

If the financial condition, F_c, falls below the poverty threshold of the year (i.e. $F_c < P_{Th}$), it is expected that farmers, who suffer from unfavourable financial conditions attempt to get out of the poverty situation. Thus, for choosing the crop type, first, the agents assess the correlation of the behavioral rules with their own social and agricultural conditions. Afterward, from the set of rules with the maximum correlation with their characteristics, the agents select the behavioral rule with the highest profit.

If F_c shows a moderately tolerable financial condition (i.e. $F_c \cong P_{Th}$), then, after assessment of the rules' correlations with their characteristics, the agents select randomly from the rules with the maximum correlation and medium to maximum profit.

Eventually, if F_c represents a satisfactory financial condition (i.e. $F_c > P_{Th}$), then, agents select randomly from the rules by only considering the highest correlation with their own properties.

After defining the crop type, the ABM commences Phase 3, the agricultural activities. In this part, farmers acquire their irrigation water need from precipitation, groundwater, surface water. The amount of irrigation water need for each agent is estimated according to the water need of the chosen crop type and the area of the agent's farmland. The effective precipitation amount covering irrigation water needs is calculated by the USDA soil conservation service method (Smith, 1992):

$$R_{\text{eff}} = 125 + 0.1R \qquad \text{for } R > 250 \text{ mm/m} \tag{4}$$

$$R_{\text{eff}} = R\,\frac{(125-0.2R)}{125} \qquad \text{for } R \leq 250 \text{ mm/m} \tag{5}$$

Where R_{eff} and R are effective precipitation and gross monthly rainfall, respectively.

Then, farmers try to obtain their remainder irrigation water need from surface water resources, Zarrineh-Rud River. Also, it has been considered that farmers use groundwater as an additional source when accessible surface water is less than their actual demand:

$$W_{GW} = I_D - W_{SW} \tag{6}$$

Where, W_{GW} is the combined illegal and legal groundwater withdrawal for irrigation, I_D is farm's net monthly crop consumptive use minus effective precipitation, and W_{SW} is withdrawn surface water.

Meanwhile, agricultural expenditures based on the selected crop type and farm's size will be paid from the agents' deposits:

$$DM_1 = DM_0 - AE_i \tag{7}$$

Where, DM_1 is the remaining money in the deposit after payment, DM_0 is the deposited money, and AE_i is average agricultural expenditures of the crop i per hectare.

Next, the crop yield for the agents, CY_a, is determined as a function of supplied water per hectare (ha) of farm as follow:

$$\left(1 - \frac{CY_a}{CY_m}\right) = K_y\,(1 - \frac{\sum ET_a}{\sum ET_m}) \tag{8}$$

where CY_a is the actual yield (kg/ha), CY_m is the maximum yield (kg/ha), K_y is the yield response factor, ET_m is the maximum crop evapotranspiration (mm/period), and ET_a is the actual crop evapotranspiration (mm/period) (Foster and Brozović, 2018; Saed et al , 2019).

In the last step of Phase 3, farmer agents sell all of their products at the selling price of the year. Then the *deposit* variable will be updated by the gained *profit.* At the end of Phase 3, an agricultural year has ended and the outcomes of the conducted processes may alter the conditions of farmer agents, which affect their decision-making process for the upcoming year. Subsequently, the model iterates the socio-hydrological loop from the first phase for the following agricultural year.

4. Results and Discussion

Using the social data gathered in the field studied, nine behavioral rules have been extrapolated by ARM for the main crop types of the study area. As stated earlier, the agents choose their behavioral profile from the rules listed in Table 2.

Table 2. The discovered rules of crop choices and farmers' characteristics.

	Alfalfa	Alfalfa	Onion	Corn	Tomato	Barely	Wheat	Sugar beet	Sugar beet
Size of the farmland			Small	Medium	Small		Large		
Having well in the farm		Yes						Yes	
Type of nearby water resources		The main irrigation canal			The main irrigation canal				The main river
Livestock farming	No		Yes			Yes			
Selling contract			No				Yes		No
Financial condition		Poor		Medium	Medium				Poor
Agricultural knowledge	Poor		Medium			Medium			
Household labor working on the farm	Yes					No		Yes	Yes
Availability of agricultural machinery							Yes		Yes
Age			Adult			Old		Old	
Location of the farmland alongside the main river channel		Near diversion dam	Upstream					Upstream	Upstream

Ownership of the farm	Rented		Owned	Owned	Owned	Owned			
Education level				High school				Primary	
Confidence of the rule	69%	82%	77%	78%	87%	79%	91%	81%	74%

Each of the rules has some degree of correlation with the characteristics of the farmer agents limiting the options for each type of agent. After agents finish their agricultural decision-making, the amount of required water for irrigation and the energy needed for agricultural activities will be determined based on the area under cultivation of each crop type. Fig. 3 illustrates the area of each crop type cultivated by agents in the ABM for 2009 to 2016 agricultural years.

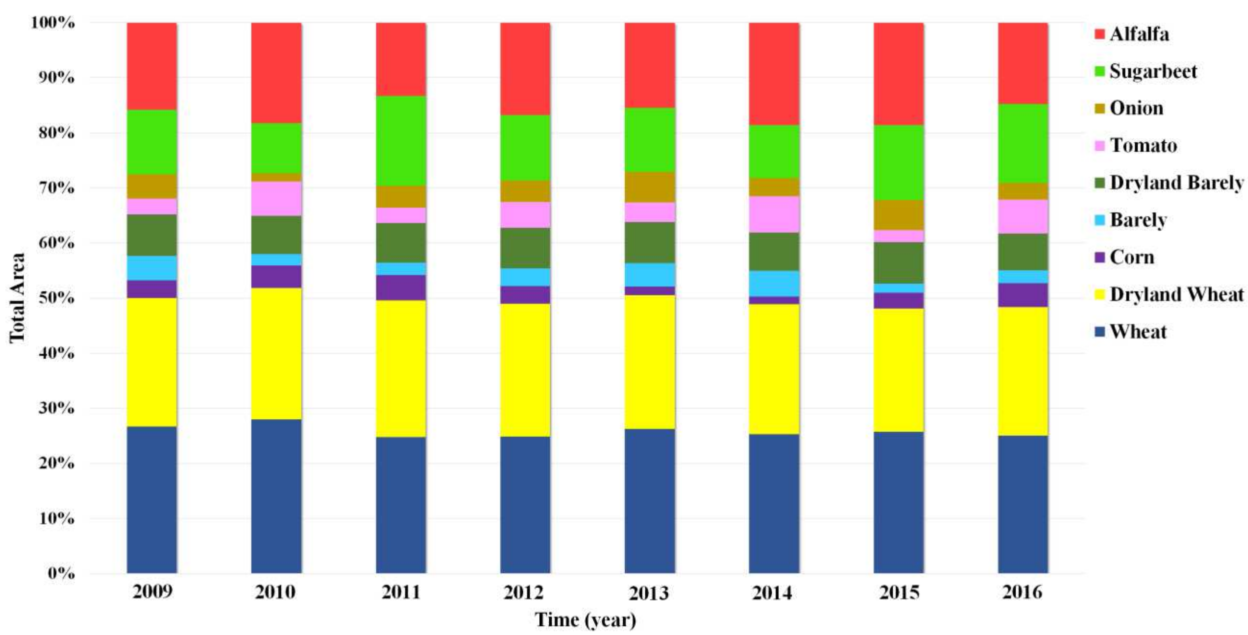

Fig. 3 Average total farming area for each crop type in ABM (in percentage)

As shown in Fig. 3, wheat is the most planted crop type in the simulation period. The underlying reason for this matter may be due to its suitableness (i.e., less required characteristics (Table 2)) for the agents representing the farmers with large farmlands and diverse characteristics, who have access to agricultural machinery. Also, according to interviewed farmers, because of assured selling price under pre-set contracts and the simplicity of farming, planting wheat is considered as a priority by most farmers, regardless of its lower selling price in comparison to sugar beet and alfalfa. The results of the ABM also indicated that water-intensive crops such as sugar beet and alfalfa were mostly selected by small-holders with unfavorable financial conditions. Furthermore, there are some mountainous areas in the region without proper access to surface water and groundwater resources. Therefore, farmers in these areas mainly have been planting wheat and corn by dryland farming, and there were no considerable changes in area or crop type in recent years due to resource limitations. In this regard, for dryland wheat and corn, statistical data have been used for some agents to represents actual farmers farming dryland wheat averagely 23% of total agricultural areas and an averagely 7% dryland corn every agricultural year.

As stated earlier, the agricultural activities in ABM affect the hydrological and energy systems. The primary energy usages in agricultural activities, which have been considered for this study, contain on-farm and off-farm consumptions (Fig. 4).

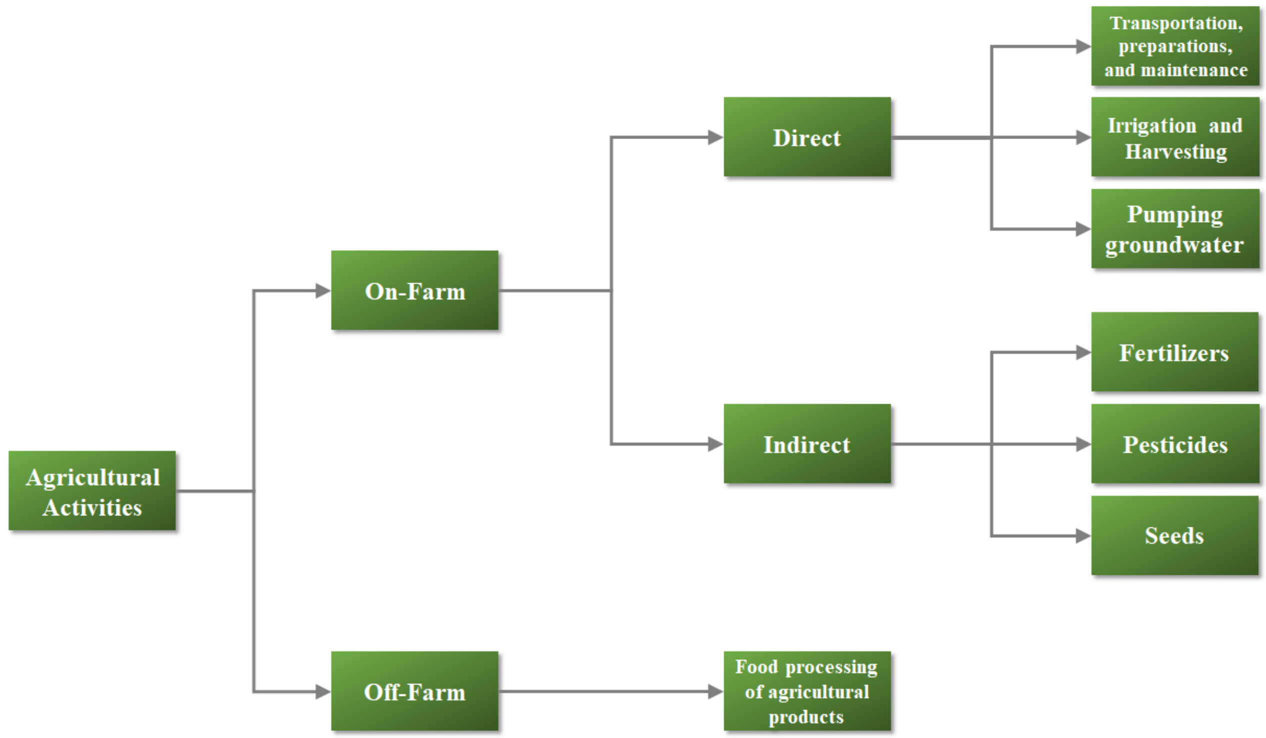

Fig. 4 The overview of energy nexus model

On-farm direct energy consumption includes: (a) fuel required for agricultural machinery in transportation, farmland's preparation, planting, and maintenance; (b) fuel required for irrigation systems and harvesting; (c) electricity for water pumps. On-farm indirect energy expenditures include: (a) consumed energy for the production of fertilizers; (b) consumed energy for the production of chemical compounds such as pesticides; (c) consumed energy for seeds. It should be noted that off-farm energy consumptions mainly cover the food processing of agricultural products and their related transportation.

4.1. Irrigation Required Energy for Groundwater Pumping

A significant amount of energy is needed to utilize groundwater resources for irrigation. Required fuel energy for irrigating one hectare of farmland depends on groundwater elevation, irrigation system type, crop water need, and equipment's power consumption. Eq. 9 represents the required energy for pumping water:

$$E_i = \rho g H Q_i / (\varepsilon_1 \times \varepsilon_2) \tag{9}$$

Where E_i indicates energy (joule per hectare) for the crop (i), ρ is water density (kg/ m^3), g is gravitational constant, H is the total dynamic head (m) including friction losses, and Q_i is annual water demand volume (m^3 per hectare) for the crop (i). ε_1 represents pump efficiency, which is generally ranged from 0.7 to 0.9 based on elevators height, water flow, and speed. ε_2 indicates the total efficiency of energy and power conversion, which is 0.18 to 0.22 for electro-pump, and 0.25 to 0.3 for diesel.

For calculating the dynamic head, the required data have been provided through field studies. It should be noted that for this case study, the Moody diagram has been used to calculate the friction loss (E_f). In the next step required energy for the pump (E_P) may be calculated through Eq. 10:

$$E_P = \left(\left(\frac{P_2}{\rho}\right) + 0.5v_2^2 + z_2 g\right) - \left(\left(\frac{P_1}{\rho}\right) + 0.5v_1^2 + z_1 g\right) + E_f \tag{10}$$

Where P is pressure, ρ is specific weight, v is speed, z is height, and g is the gravitational acceleration. Since flow speed in the given aquifer is negligible, it has been considered that $v_1 = v_2 = 0$. Groundwater irrigation required energy has been obtained for each crop type, considering $\varepsilon_1 = 0.8$ و $\varepsilon_2 = 0.2$ (see Table 3).

Table 3. The amount of required water and the energy needed for irrigation of each crop type

	$Q\ (\frac{m3}{ha})$	$E\ (\frac{MJ}{ha})$
Wheat	2379	3066.03
Alfalfa	5969	7692.78
Sugar beet	5665	7300.99
Barely	1734	2234.76
Tomato	4488	5784.08
Onion	4941	6367.91
Corn	3817	4919.31

4.2. Energy Consumption of Machinery Operations

Required fuel per hectare of farmland varies based on the type of agricultural machinery, soil condition, crop type, etc. To determine consumed fuel, at first, the necessary power for the movement of machinery in the farmland should be calculated. Table 4 represents the required traction force of plough for per unit area of soil, including disc, cultivator, and planter for per unit width of the machine.

Table 4. The required traction force of agricultural machinery (Kepner et al., 1982)

Machine	Required power
Plough	3.4~6.2 (N/Cm2)
Tandem disc	1.5~2.9 (KN/m)
Offset disc	3.6~5.8 (KN/m)
Cultivator	0.6~1.2 (KN/m)
Planter	0.45~0.8 (KN/row)
Grain Drills	0.4~1.5 (KN/m)
Rotary cultivator	17~24 (N/Cm)

After obtaining the required traction force, the drawbar power (P_M) should be calculated by Eq. 11. Where P_M is drawbar power (kW), F_M is drawbar force (kN), and V is the movement speed (km/h).

$$P_M = (F_M * V)/3.6 \tag{11}$$

The P_M is always less than Power-Take-Off (PTO) output because of drive wheel slippage, tractor rolling resistance, and friction losses in the drive train between the engine and the wheels. The sum of these losses may be represented by a Tractive & Transmission (T&T) coefficient (see Eq. 12). The values of the $T\&T$ coefficient for different soil types and different work conditions are represented in Table 5. After determining PTO, the percentage of load on the engine (PLE) may be defined by Eq. 13.

$$\text{T\&T} = \frac{drawbar\ power\ (P_M)}{PTO} \tag{12}$$

$$PLE = \frac{P_M}{Maximum\ amount\ of\ P_M} \tag{13}$$

Table 5. *T&T* coefficients in different soils and different loads

Plain type	Light load	Medium load	Heavy load
Concrete	0.75	0.85	0.9
Non-tillage land	0.6	0.75	0.8
Tillage land	0.4	0.6	0.65
Fresh tillage land	0.25	0.4	0.45

Generally, the maximum amount of P_M is considered as 80~90% of the tractor's nominal power. Regarding the type of tractor, *MF285*, which is mainly used by the farmers of the given study area, and its nominal power of 75 horsepower (55.86 kW), the maximum amount of P_M is 47.5kW.

Table 6 represents the values of fuel efficiency (kWh/liter) for different imposed loads on the engine. It should be noted that other loads may be calculated through interpolation of the presented values. Then, to determine the consumed fuel per hour for each operation, P_M will be divided into the value of fuel efficiency.

Table 6. The values of tractor's fuel efficiency of full gas mode (kW.h/liter) (Hunt, 2008)

Percentage of the imposed load on engine	Normal diesel engine
100	2.9
80	2.84
60	2.6
40	2.13
20	1.38

In this regard, the amount of consumed fuel in each operation have been calculated and presented in Table 7. It should be noted the required fuel for harvesting machinery has been considered equal to the relative operation according to the type of the employed tractor.

Table 7. Average required energy for agricultural operations

Operation	Traction force (kN)	drawbar power (kN)	T&T coefficient	P_M (kW)	Load	Fuel efficiency (kW.h/liter)	Fuel consumption (liter/h)	Total operation time (h)	Required fuel (liter)
Tillage	18.4	25.5	0.8	32	0.65	2.65	12.07	4	48.28
Disk	8.5	14.1	0.45	31.3	0.64	2.65	11.8	3	35.4
Land leveling	8.5	14.1	0.45	31.3	0.64	2.65	11.8	4	47.2
Fertilization	-	-	-	9.7	0.2	1.38	7	2	14
Planting	3.6	7	0.4	17.5	0.36	2.1	8.3	3	24.9
Insecticide	-	-	-	9.7	0.2	1.38	7	2	14
Weeding	2.4	2.7	0.4	6.7	0.14	1.15	5.8	6	34.8
harvesting	-	-	-	-	-	-	12.07	5	60.35
Total required fuel	-	-	-	-	-	-	-	-	278.93

4. 3. Relative Energy of Seed, Pesticide, and Fertilizer

Based on the field studies and the farming system of the given region, the relative energy of the production of seed, pesticide, and fertilizer have been determined and presented in Table 8.

Table 8. Energy inputs of seeds, pesticides, and fertilizers in the cultivation of one hectare of different crops in the study area

Crop	Seed (kg)		Nitrogen (kg)		Phosphate (kg)		Potassium (Kg)		Pesticide (Diazinon) (lit)		Fungicide (Carboxin) (kg)	
	Quantity per unit area (ha)	Energy equivalent (MJ /unit)	Quantity per unit area (ha)	Energy equivalent (MJ /unit)	Quantity per unit area (ha)	Energy equivalent (MJ /unit)	Quantity per unit area (ha)	Energy equivalent (MJ /unit)	Quantity per unit area (ha)	Energy equivalent (MJ /unit)	Quantity per unit area (ha)	Energy equivalent (MJ /unit)
Wheat	293.5	20.21	161.9	78.1	137.4	17.4	106.2	13.7	1.2	101.2	2	216.9
Dry-Wheat	50.5	20.21										
Alfalfa	48.07	6.9	92	78.1	57.5	17.4	138	13.7	0.5	101.2	1	216.9
Sugarbeet	50	2.9	119.3	78.1	25.8	17.4	11.3	13.7	1	101.2	1.3	216.9
Barely	232.7	14.7	183.4	78.1	121.3	17.4	91.7	13.7	1.7	101.2	2.7	216.9
Dry-Barely	58	14.7										
Onion	11.1	14.7	219	78.1	183	17.4	109	13.7	3.55	101.2	1.63	216.9
Tomato	0.3	1	406.4	78.1	418.5	17.4	105.5	13.7	2.2	101.2	2.2	216.9
Corn	51.7	14.7	173.1	78.1	90.5	17.4	57.5	13.7	1.6	101.2	3.1	216.9

Figs. 5 and 6 demonstrate the amount of water need and energy need for the agricultural area. According to Fig. 6, 2014 was one of the aridest years of the study area. Respectively, the amount of groundwater extractions was at its highest in the study period. Therefore, more energy has been consumed for pumping groundwater, which significantly raised the energy consumption in 2014. On the other hand, energy consumption was at its lowest rate in 2011, which may be due to lower groundwater extractions and lower cultivation areas of crop types such as alfalfa and tomato (see Fig. 3). It should be noted, the alfalfa is one of the most water-intensive crop types in the study region, which contributes to the drought of the Urmia Lake. Additionally, the cultivation of tomato requires higher amounts of fertilizers and pesticides in comparison to other crop types, providing which consume more energy. Moreover, as surface water resources become less accessible, there would be more groundwater exploitations following with higher energy consumptions.

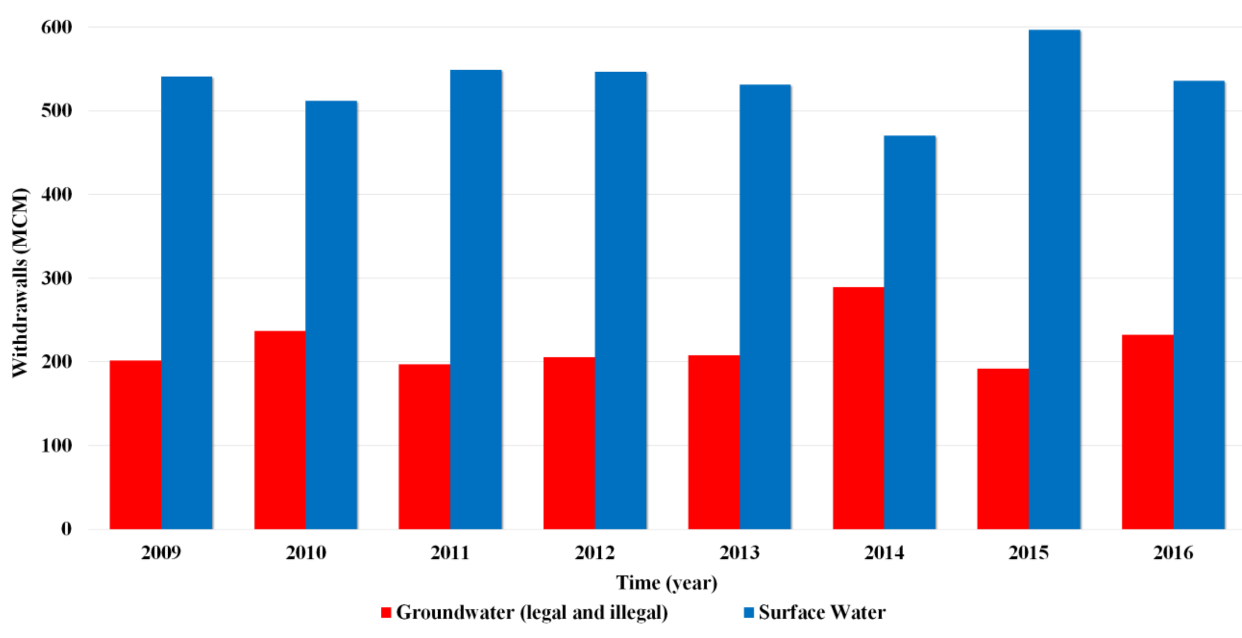

Fig. 5 The water need for 2009 to 2016 agricultural years

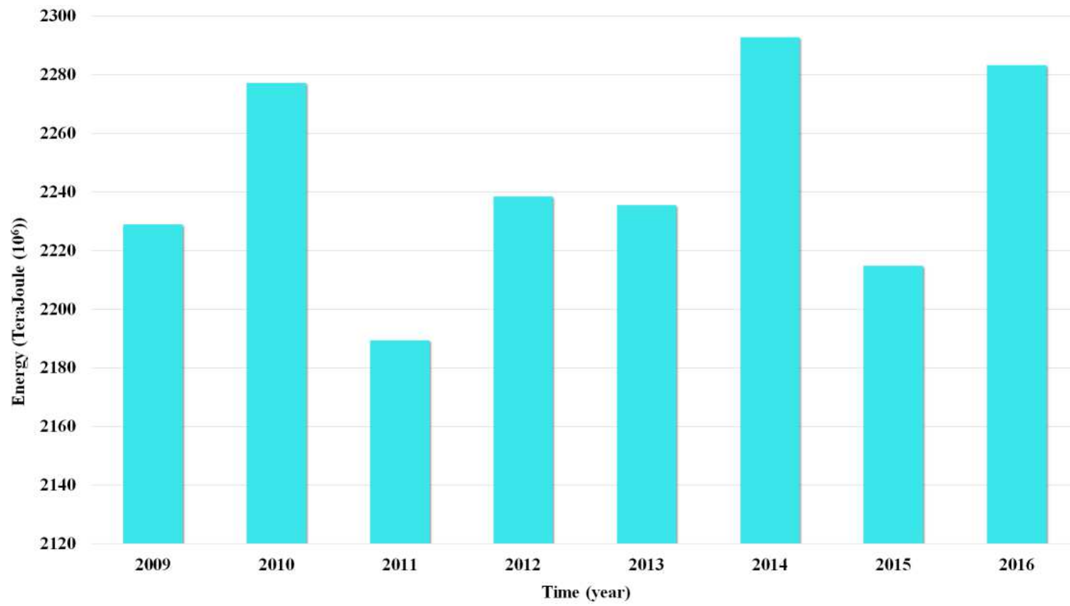

Fig. 6 The energy need for 2009 to 2016 agricultural years

Regarding Fig. 5, one of the leading water governance challenges in the study area is the increasing number of illegal water wells. According to ULRP (2015), there were approximately 45 000 illegal water wells in Urmia Lake Basin, which have the potential to be increased in the present and the future, since farmers dig deeper and install larger pumps as the groundwater level drops. In addition to the limitations of surface water use, another factor leading farmers to over-extract groundwater resources is the economic decline. In recent decades, the Iran national currency have been devaluated significantly due to economic embargos, which through an increase in living expenses have affected farmers' livelihood. Therefore, most of the farmers with the unfavorable financial condition, especially small-holders, switched their crop type to water-intensive ones such as alfalfa or sugar beet because of their higher profit. Respectively, to supply water need for irrigation, regarding limitations in withdrawing from surface water resources and heightening economic difficulties, over-extractions of groundwater resources have caused a considerable increase in energy consumption as well.

5. Conclusion

It has been argued, demand for freshwater, energy, and food will be significantly increased due to population growth and following rapid anthropogenic changes and developments. Respectively, the capacity of water resources to sustain environmental and human needs is of paramount concern of policy-makers, as its condition, directly and indirectly, affects food production, energy systems, and ecosystems. Thus, due to the interdependence of water-food-energy (WEF), many studies indicated that improper management strategies that cover the whole system of WEF and also lack of flexibility against dynamic changes might threaten the availability of natural resources for the future generations.

Regarding the increasing anthropogenic stresses on ecological systems, future studies should explore the interactions between social and environmental systems more in-depth. To this end, the current study presents a novel framework to investigate how farmers' decision-making and activities affect the WEF nexus. In this way, an agent-based model (ABM) representing the human system, and a system-dynamic model (SD) representing interactions between food, water, and energy systems have been integrated and applied on the Zarrineh-Rud River Basin. The outcomes of this study indicated that how farmers' choices and dynamic activities can significantly affect food production, water resources, and energy systems. Thus, it is essential to consider various aspects of social systems in future WEF nexus studies.

Declarations

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Conflicts of interest/Competing interests

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Not applicable

Consent to participate

Not applicable

Consent for publication

The authors give their full consent for the publication of this manuscript.

Availability of data and material

Not applicable

Code availability

Not applicable

Authors' contributions

Amir Molajou: Conceptualization, Formal analysis, Writing - original draft

Abbas Afshar: Supervision, Methodology, Review & Editing

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References

1. AghaKouchak, A., Feldman, D., Hoerling, M., Huxman, T. and Lund, J., 2015. Water and climate: Recognize anthropogenic drought. *Nature News, 524*, pp.409-411.
2. Al-Saidi, M., & Elagib, N. A. (2017). Towards understanding the integrative approach of the water, energy and food nexus. *Science of the Total Environment*, *574*, 1131-1139.
3. Ashraf, S., AghaKouchak, A., Nazemi, A., Mirchi, A., Sadegh, M., Moftakhari, H. R., ... & Anjileli, H. (2019). Compounding effects of human activities and climatic changes on surface water availability in Iran. *Climatic change*, *152*(3-4), 379-391.
4. Bakarji, J., O'Malley, D., & Vesselinov, V. V. (2017). Agent-based socio-hydrological hybrid modeling for water resource management. *Water Resources Management*, *31*(12), 3881-3898.
5. Biba, S. (2016). The goals and reality of the water–food–energy security nexus: the case of China and its southern neighbours. *Third World Quarterly*, *37*(1), 51-70.
6. Biggs, E. M., Bruce, E., Boruff, B., Duncan, J. M., Horsley, J., Pauli, N., ... & Haworth, B. (2015). Sustainable development and the water–energy–food nexus: A perspective on livelihoods. *Environmental Science & Policy*, *54*, 389-397.
7. Cai, X., Wallington, K., Shafiee-Jood, M., & Marston, L. (2018). Understanding and managing the food-energy-water nexus–opportunities for water resources research. *Advances in Water Resources*, *111*, 259-273.
8. Daher, B. T., & Mohtar, R. H. (2015). Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. *Water International*, *40*(5-6), 748-771.

9. Dang, Q., & Konar, M. (2018). Trade openness and domestic water use. *Water Resources Research*, *54*(1), 4-18.
10. De Grenade, R., House-Peters, L., Scott, C. A., Thapa, B., Mills-Novoa, M., Gerlak, A., & Verbist, K. (2016). The nexus: reconsidering environmental security and adaptive capacity. *Current opinion in environmental sustainability*, *21*, 15-21.
11. de Vito, R., Portoghese, I., Pagano, A., Fratino, U., & Vurro, M. (2017). An index-based approach for the sustainability assessment of irrigation practice based on the water-energy-food nexus framework. *Advances in Water Resources*, *110*, 423-436.
12. Di Baldassarre, G., Sivapalan, M., Rusca, M., Cudennec, C., Garcia, M., Kreibich, H., ... & Sanderson, M. R. (2019). Sociohydrology: Scientific challenges in addressing the sustainable development goals. *Water Resources Research*, *55*(8), 6327-6355.
13. Emami, F. and Koch, M., 2018. Agricultural water productivity-based hydro-economic modeling for optimal crop pattern and water resources planning in the Zarrine River Basin, Iran, in the wake of climate change. *Sustainability*, *10*(11), pp.1-35.
14. Endo, A., Tsurita, I., Burnett, K., & Orencio, P. M. (2017). A review of the current state of research on the water, energy, and food nexus. *Journal of Hydrology: Regional Studies, 11,* 20-30.
15. Foran, T. (2015). Node and regime: Interdisciplinary analysis of water-energy-food nexus in the Mekong region. *Water Alternatives*, *8*(1).
16. Foster, T. and Brozović, N., 2018. Simulating Crop-Water Production Functions Using Crop Growth Models to Support Water Policy Assessments. *Ecological Economics*, *152*, pp.9-21.

17. Ghale, Y. A. G., Altunkaynak, A., & Unal, A. (2018). Investigation anthropogenic impacts and climate factors on drying up of Urmia Lake using water budget and drought analysis. *Water resources management*, *32*(1), 325-337.

18. Gocsik, É., Saatkamp, H. W., De Lauwere, C. C., & Lansink, A. O. (2014). A conceptual approach for a quantitative economic analysis of farmers' decision-making regarding animal welfare. *Journal of agricultural and environmental ethics*, *27*(2), pp. 287-308.

19. Han, J., Kamber, M., & Pei, J. (2006). Data mining: concepts and techniques. 2001. *San Francisco: Morgan Kauffman.*

20. Henareh Khalyani, A., Mayer, A. L., & Norman, E. S. (2014). Water flows toward power: socioecological degradation of Lake Urmia, Iran. *Society & Natural Resources*, *27*(7), pp. 759-767.

21. Hoff, H., 2011. Understanding the Nexus, Background Paper for the Bonn Conference 2011: the Water-energy-food Security Nexus. Stockholm, Stockholm Environment Institute

22. Howells, M., Hermann, S., Welsch, M., Bazilian, M., Segerström, R., Alfstad, T., ... & Wiberg, D. (2013). Integrated analysis of climate change, land-use, energy and water strategies. *Nature Climate Change*, *3*(7), 621-626.

23. Hunt, D. (2008). *Farm power and machinery management*. Waveland Press.

24. Jepsen, M. R., Leisz, S., Rasmussen, K., Jakobsen, J., MØller-Jensen, L., & Christiansen, L. (2006). Agent-based modelling of shifting cultivation field patterns, Vietnam. *International Journal of Geographical Information Science*, *20*(9), pp. 1067-1085.

25. Karnib, A. (2018). Bridging science and policy in water-energy-food nexus: using the Q-Nexus model for informing policy making. *Water Resources Management*, *32*(15), 4895-4909.

26. Kepner, R. A., Bainer, R., & Barger, E. L. (1982). Principles of farm machinery third edition, third reprint.

27. Khazaei, B., Khatami, S., Alemohammad, S. H., Rashidi, L., Wu, C., Madani, K., ... & Aghakouchak, A. (2019). Climatic or regionally induced by humans? Tracing hydro-climatic and land-use changes to better understand the Lake Urmia tragedy. *Journal of hydrology*, *569*, 203-217.

28. Kuil, L., Carr, G., Prskawetz, A., Salinas, J. L., Viglione, A., & Blöschl, G. (2019). Learning from the Ancient Maya: Exploring the impact of drought on population dynamics. *Ecological economics*, *157*, 1-16.

29. Kurian, M. (2017). The water-energy-food nexus: trade-offs, thresholds and transdisciplinary approaches to sustainable development. *Environmental Science & Policy*, *68*, 97-106.

30. Li, M., Fu, Q., Singh, V. P., Ji, Y., Liu, D., Zhang, C., & Li, T. (2019b). An optimal modelling approach for managing agricultural water-energy-food nexus under uncertainty. *Science of the Total Environment*, *651*, 1416-1434.

31. Li, M., Fu, Q., Singh, V. P., Liu, D., & Li, T. (2019a). Stochastic multi-objective modeling for optimization of water-food-energy nexus of irrigated agriculture. *Advances in Water Resources*, *127*, 209-224.

32. Molajou, A., Afshar, A., Khosravi, M., Soleimanian, E., Vahabzadeh, M., & Variani, H. A. (2021). A new paradigm of water, food, and energy nexus. *Environmental Science and Pollution Research*, 1-11. https://doi.org/10.1007/s11356-021-13034-1
33. Newell, J. P., Goldstein, B., & Foster, A. (2019). A 40-year review of food–energy–water nexus literature and its application to the urban scale. *Environmental Research Letters*, *14*(7), 073003.
34. Nourani, V. and Molajou, A., 2017. Application of a hybrid association rules/decision tree model for drought monitoring. *Global and Planetary Change*, *159*, 37-45.
35. Nourani, V., Sattari, M. T., & Molajou, A. (2017). Threshold-based hybrid data mining method for long-term maximum precipitation forecasting. *Water Resources Management*, *31*(9), 2645-2658.
36. Panahi, D. M., Kalantari, Z., Ghajarnia, N., Seifollahi-Aghmiuni, S., & Destouni, G. (2020). Variability and change in the hydro-climate and water resources of iran over a recent 30-year period. *Scientific Reports*, *10*(1), 1-9.
37. Ramaswami, A., Boyer, D., Nagpure, A. S., Fang, A., Bogra, S., Bakshi, B., ... & Rao-Ghorpade, A. (2017). An urban systems framework to assess the trans-boundary food-energy-water nexus: implementation in Delhi, India. *Environmental Research Letters*, *12*(2), 025008.
38. Saed, B., Afshar, A., Jalali, M. R., Ghoreishi, M., & Aminpour Mohammadabadi, P. (2019). A water footprint based hydro-economic model for minimizing the blue water to green water ratio in the Zarrinehrud river-basin in Iran. *AgriEngineering*, *1*(1), 58-74.

39. Scott, C. A., Crootof, A., & Kelly-Richards, S. (2016). The Urban Water–Energy Nexus: Building Resilience for Global Change in the “Urban Century”. In *Environmental resource management and the nexus approach* (pp. 113-140). Springer, Cham.

40. Scott, C. A., Kurian, M., & Wescoat, J. L. (2015). The water-energy-food nexus: Enhancing adaptive capacity to complex global challenges. In *Governing the nexus* (pp. 15-38). Springer, Cham.

41. Shang, Y., Hei, P., Lu, S., Shang, L., Li, X., Wei, Y., ... & Lei, X. (2018). China’s energy-water nexus: Assessing water conservation synergies of the total coal consumption cap strategy until 2050. *Applied Energy*, *210*, 643-660.

42. Smith, M. (1992). *CROPWAT: A computer program for irrigation planning and management* (No. 46). Food & Agriculture Org.

43. Spiegelberg, M., Baltazar, D. E., Sarigumba, M. P. E., Orencio, P. M., Hoshino, S., Hashimoto, S., ... & Endo, A. (2017). Unfolding livelihood aspects of the water–energy–food nexus in the dampalit watershed, Philippines. *Journal of Hydrology: Regional Studies, 11*, 53-68.

44. Taniguchi, M., Endo, A., Gurdak, J. J., & Swarzenski, P. (2017). Water-Energy-Food Nexus in the Asia-Pacific Region. *Journal of Hydrology: Regional Studies, 11*,1-8.

45. Tian, H., Lu, C., Pan, S., Yang, J., Miao, R., Ren, W., ... & Melillo, J. (2018). Optimizing resource use efficiencies in the food–energy–water nexus for sustainable agriculture: From conceptual model to decision support system. *Current Opinion in Environmental Sustainability*, *33*, 104-113.

46. ULRP - Urmia Lake Restoration Program. (2015). Urmia Lake restoration program. Brief Report and Projects Outline.

47. ULRP (Urmia Lake Restoration Program), 2017. Challenges of Urmia Lake and Restoration Program International Cooperation Division; *International Cooperation Division: Tehran, Iran*.

48. United Nations, 2016. Agriculture development, food security and nutrition, Report of the Secretary General, Item 25. 71st Session of the UN General Assembly, New York.

49. Waughray, D. (2011). *Water security the water-food-energy-climate nexus: the World Economic Forum water initiative* (No. 333.91 W3).

50. White, D. J., Hubacek, K., Feng, K., Sun, L., & Meng, B. (2018). The Water-Energy-Food Nexus in East Asia: A tele-connected value chain analysis using inter-regional input-output analysis. *Applied Energy*, *210*, 550-567.

51. Wolfe, M. L., Ting, K. C., Scott, N., Sharpley, A., Jones, J. W., & Verma, L. (2016). Engineering solutions for food-energy-water systems: it is more than engineering. *Journal of Environmental Studies and Sciences*, *6*(1), 172-182.

52. Yang, Y. E., Ringler, C., Brown, C., & Mondal, M. A. H. (2016). Modeling the agricultural water–energy–food nexus in the Indus River Basin, Pakistan. *Journal of Water Resources Planning and Management*, *142*(12), 04016062.

53. Yekom Consulting Engineering Company, 2016a. Executive solutions for 40 percent reduction in irrigation water demand, The Zarrineh-Rud River and Simineh-Rud River basin, Volume 2: The current situation and proposed plan. Iran Ministry of Energy (In Persian).

54. Yekom Consulting Engineering Company, 2016b. Executive solutions for 40 percent reduction in irrigation water demand, The Zarrineh-Rud River and Simineh-Rud River

basin, Volume 3: Social characteristics, operating scheme, and assessment of the cooperation of stakeholders. Iran Ministry of Energy (In Persian).

55. Zhang, X., & Vesselinov, V. V. (2017). Integrated modeling approach for optimal management of water, energy and food security nexus. *Advances in Water Resources*, *101*, 1-10.

Figures

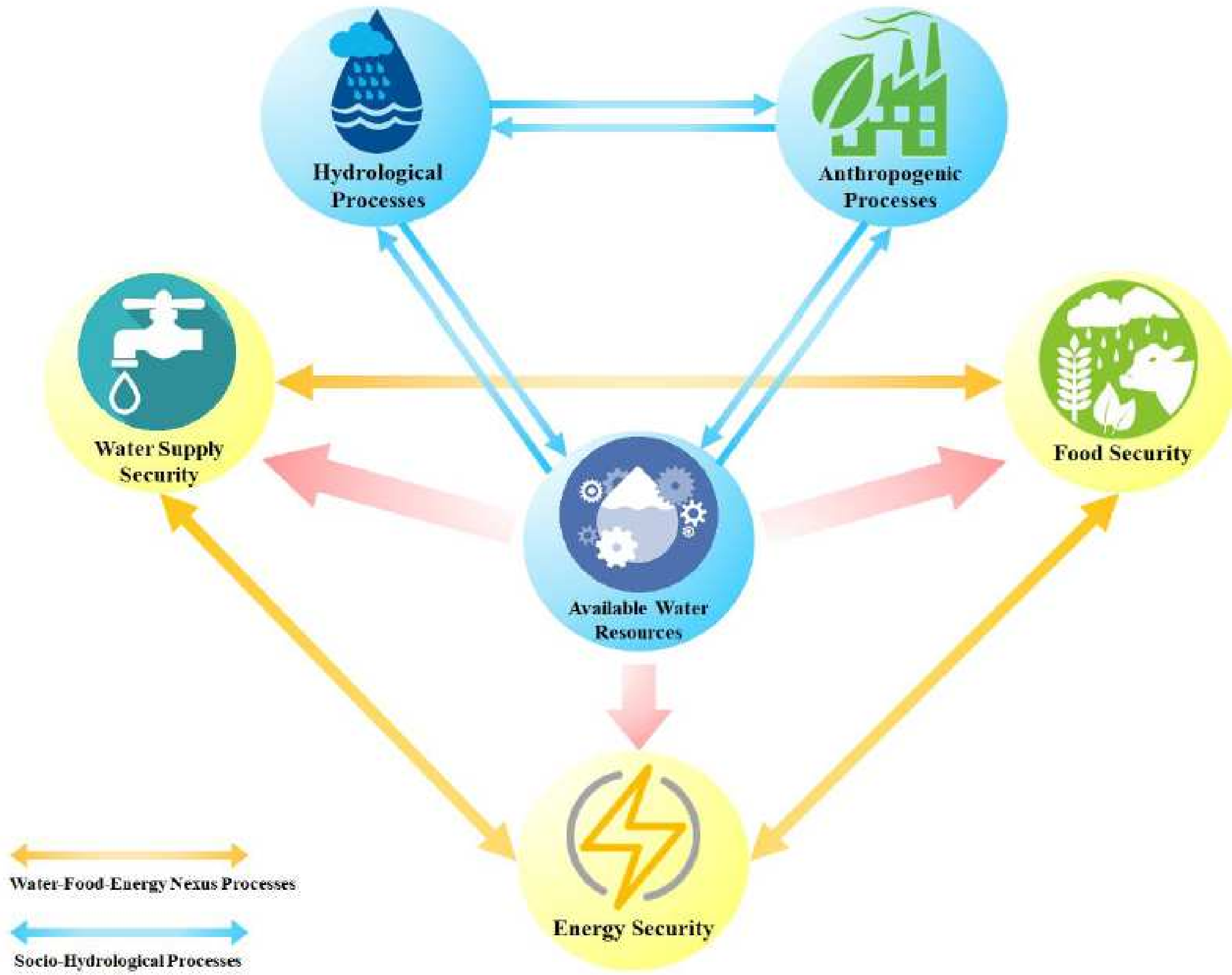

Figure 1

The conceptual framework of socio-hydrological WEF nexus system

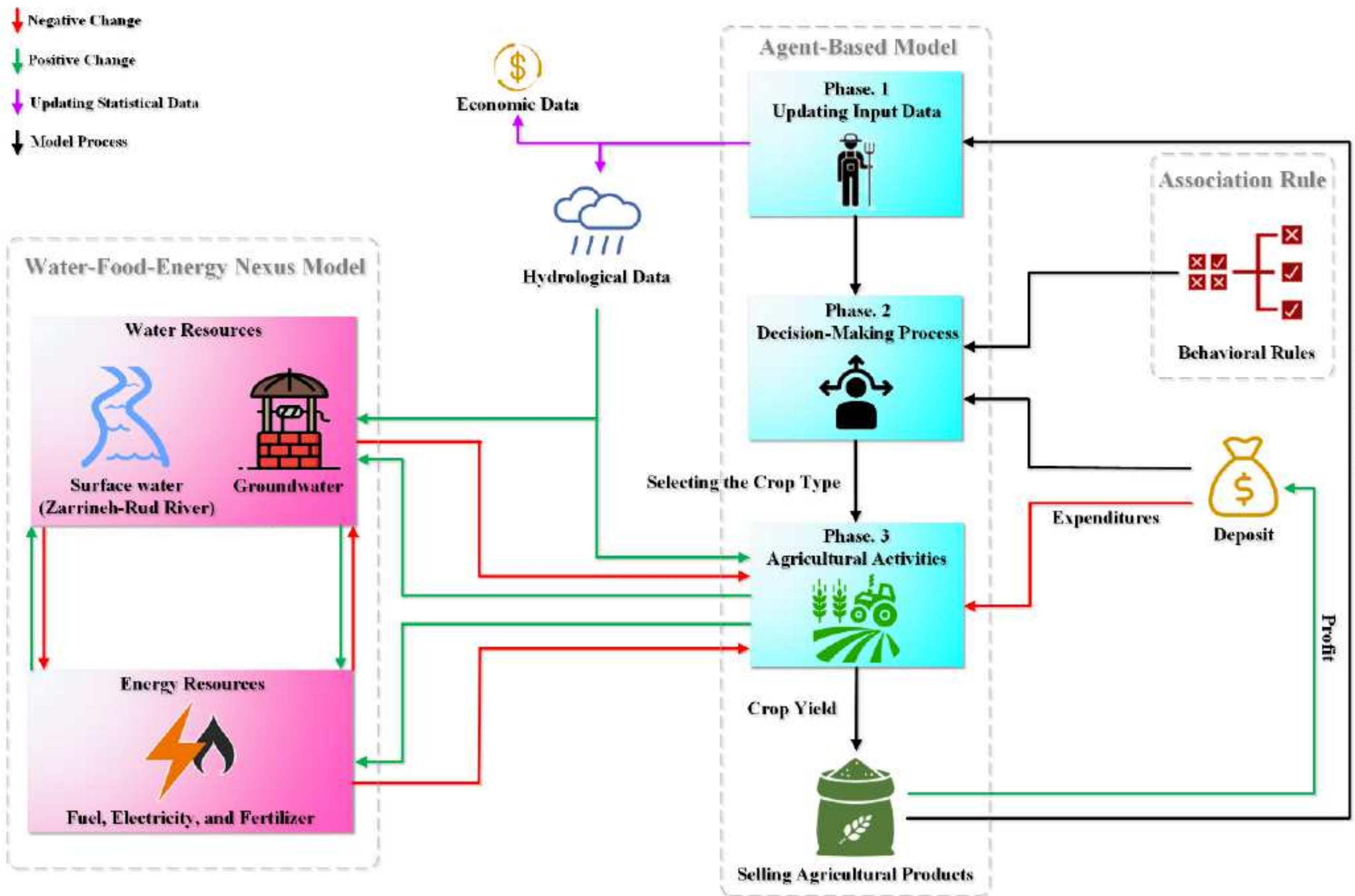

Figure 2

The schematic overview of socio-hydrological WEF nexus simulation model

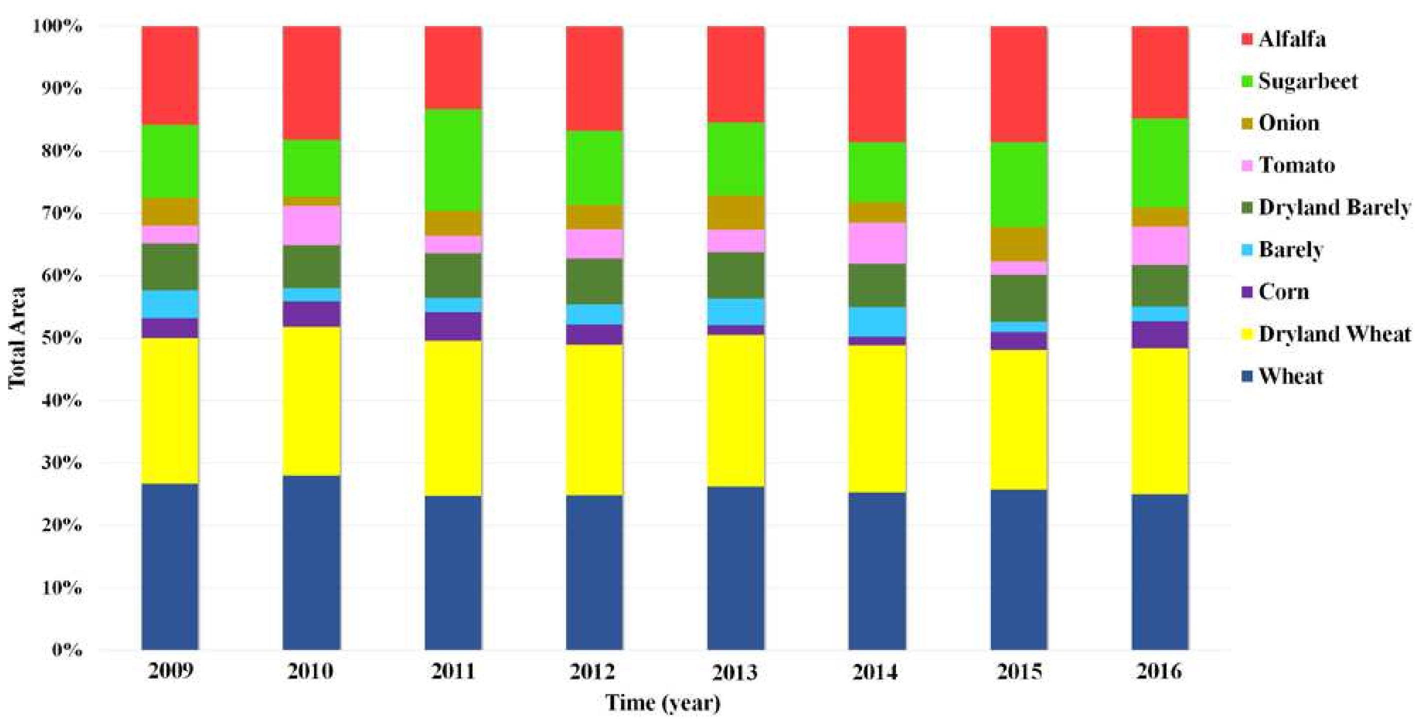

Figure 3

Average total farming area for each crop type in ABM (in percentage)

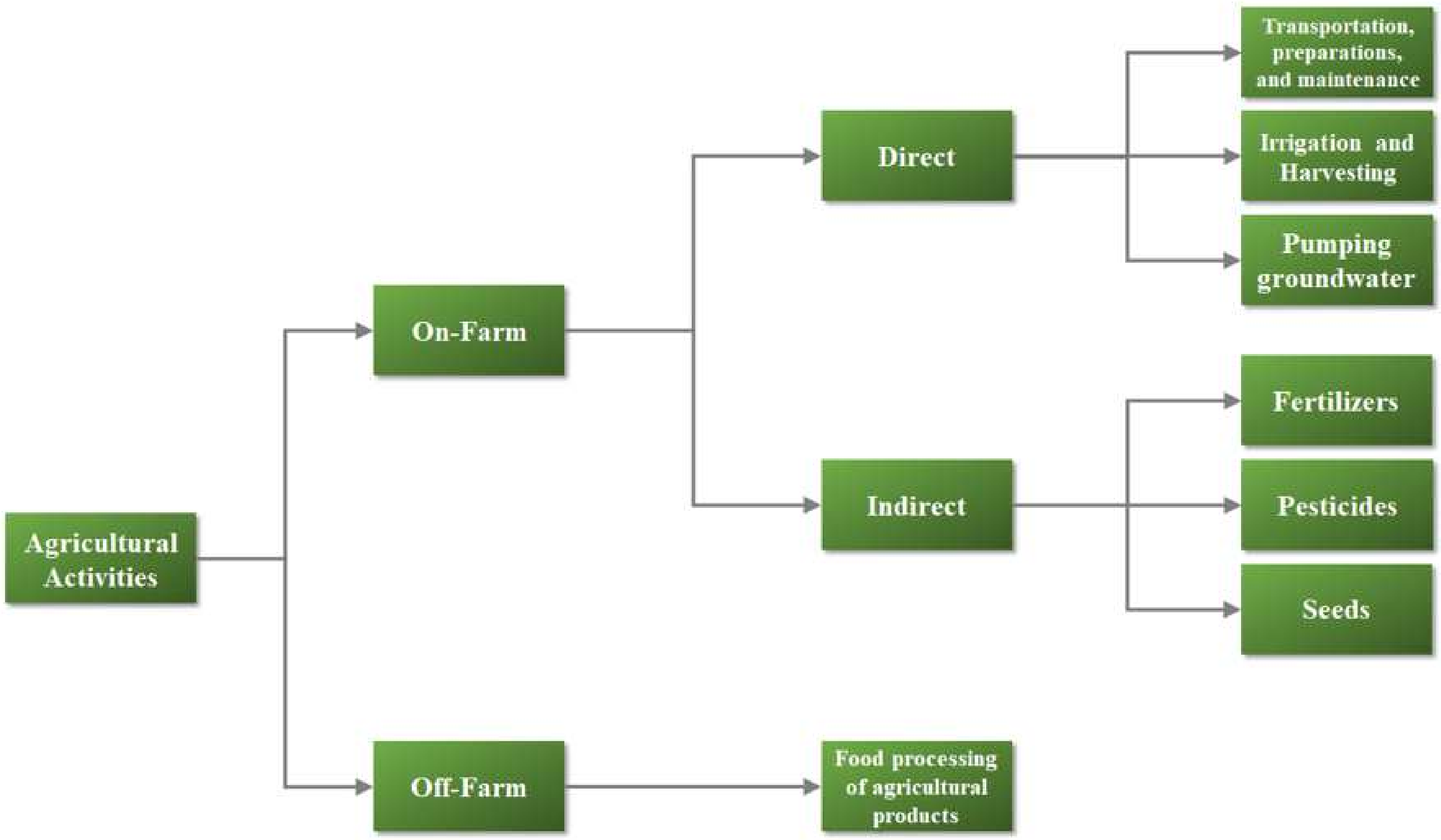

Figure 4

The overview of energy nexus model

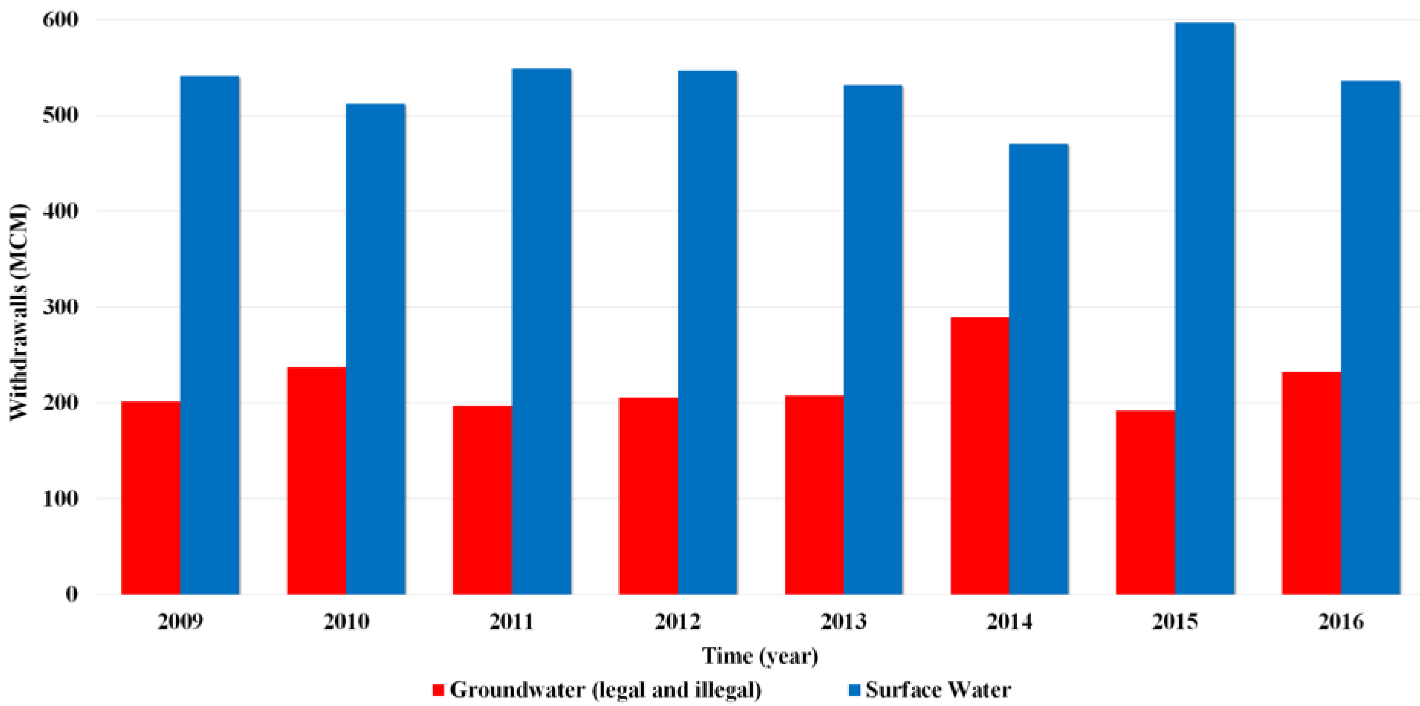

Figure 5

The water need for 2009 to 2016 agricultural years

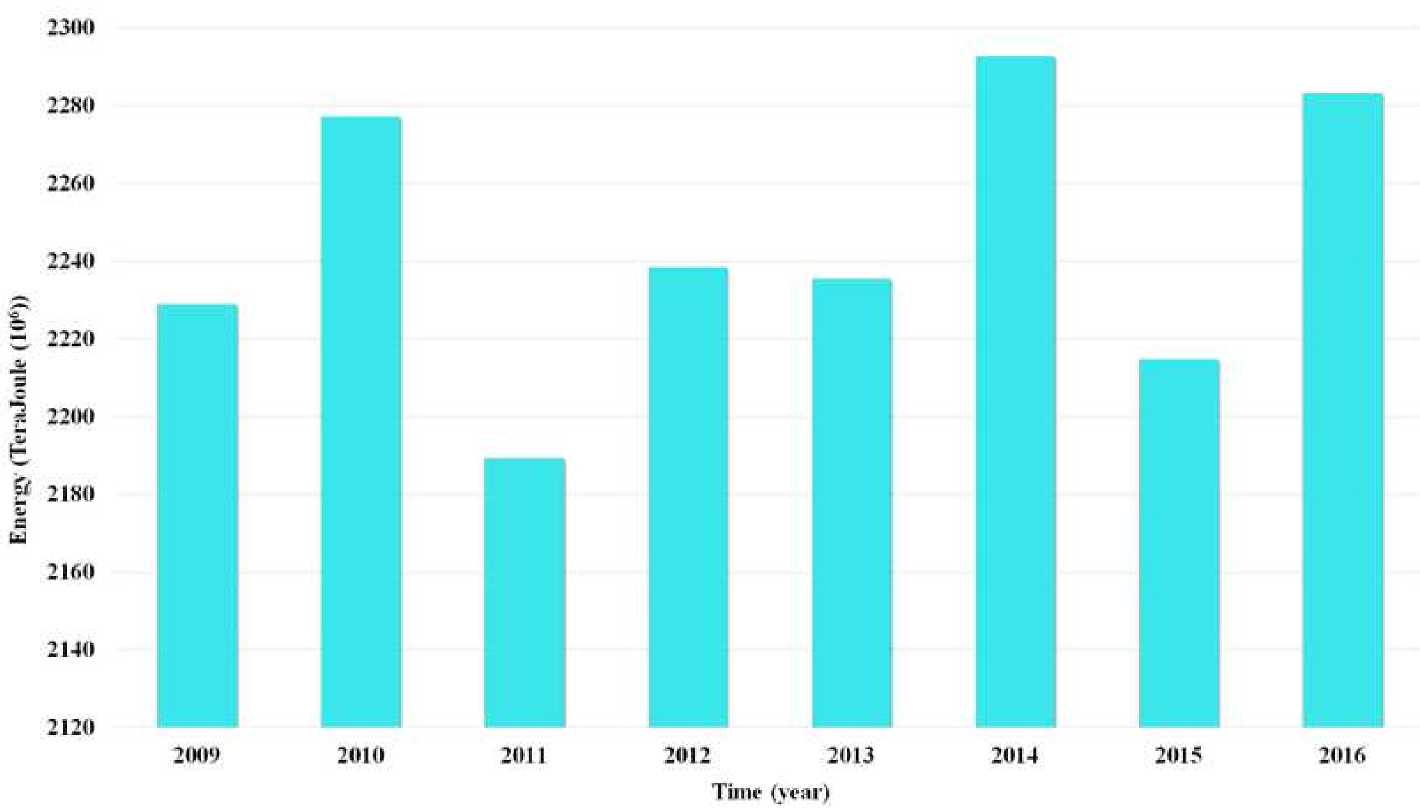

Figure 6

The energy need for 2009 to 2016 agricultural years