An integrated model to evaluate water-energy-food nexus at a household scale

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Abstract

To achieve a sustainable supply and effectively manage water, energy and food (WEF) demand, interactions between WEF need to be understood. This study developed an integrated model, capturing the interactions between WEF at end-use level at a household scale. The model is based on a survey of 419 households conducted to investigate WEF over winter and summer for the city of Duhok, Iraq. A bottom-up approach was used to develop this system dynamics-based model. The model estimates WEF demand and the generated organic waste and wastewater quantities. It also investigates the impact of change in user behaviour, diet, income, family size and climate.

The simulation results show a good agreement with the historical data. Using the model, the impact of Global Scenario Group (GSG) scenarios was investigated. The results suggest that the 'fortress world' scenario (an authoritarian response to the threat of breakdown) had the highest impact on WEF.

Keywords: end-use; household scale; income; seasonal variability; system dynamics modelling; water-energy-food Nexus

1 INTRODUCTION

Water, energy and food resources are key for satisfying the basic human needs. Global demand for these rapidly increases while billions of people are still lacking access to these resources (Bazilian et al., 2011). The main drivers behind increased demand for water, energy and food are population growth, urbanisation, economic growth and climate change (Bonn Conference, 2011; World Economic Forum, 2011).

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Households consume considerable quantities of resources (water, food and energy) to meet everyday demand of inhabitants. The household is a unit of demand and it can also be the most appropriate unit for influencing consumption practices. A high portion of water, energy and food consumption in the cities can be attributed to household uses. For instance, energy consumption at a household level in Burkina Faso and Duhok in Iraq accounts approximately 75% (Hermann et al., 2012) and 80% (General Directorate of Duhok Electricity, 2014) of the total city consumption, respectively. Most studies investigated the Nexus at the national and international scale, while limited attention has been paid to the interactions between water, energy and food at a household scale (Djanibekov et al., 2016; Endo et al., 2015; Loring et al., 2013). A single element of the nexus has been addressed in some studies. For example, Cominola et al. (2016) and Daioglou et al. (2012) modelled domestic water demand at end-use level. Sarker and Gato-Trinidad (2015) developed a model for household water demand estimation in Yarra Valley Water, Australia at end-use level. However, their model did not include garden watering end-use. Additionally, energy consumption and associated emissions from a household in Delhi is modelled by Kadian et al. (2007). They considered the impact of income and family size on energy consumption. Aydinalp et al. (2002) modelled domestic energy consumption at end-use level.

The interactions between water and energy at a household level have not been addressed very intensively (Kenway et al., 2013). For example, Cheng (2002) analysed water-related energy in residential buildings in Taiwan. They found that 88% of water-related energy use is attributed to water heating and household water pumping, while the rest is used for water treatment, water supply and wastewater treatment. Arpke and Hutzler (2006) modelled four household types and showed that 97% of water-related energy is attributed to water heating. Based on this model, Flower (2009) simulated water heating-related energy in Victoria, Australia using electricity and gas heater. Kenway et al. (2013) developed a model to investigate the energy use for household water heating in Brisbane, Australia, without considering the impact of household characteristics. They found that the household is the key driver for energy consumption and associated greenhouse gas emissions in the city.

Additionally, Abdallah and Rosenberg (2012) developed an approach to model household indoor water and energy use and their interactions. Their approach considers the impact of behavioural and technological water and energy use factors that affect the indoor use. Ren et al. (2013) developed a tool to predict the energy consumption at end-use level and related greenhouse gas emissions of Australian households, considering the impact of household occupancy patterns. However, their model does not address the seasonal variation of energy consumption. A residential end-use model was developed to estimate cold (indoor and outdoor) and hot water demand as well as wastewater generated for each month of the year (Jacobs and Haarhoff, 2004). This model highlights the impact of seasonal variability on water consumption.

Moreover, some studies addressed food consumption at a household scale. Demerchant (1997) investigated the user's influence on the energy consumption of the cooking system using electricity. The possibility to reduce the electricity use for food preparation is investigated by Wallgren and Höjer (2009). They suggested that using a microwave oven is more energy-efficient than a conventional oven for cooking some types of food. Additionally, an electric kettle consumes less energy for boiling water than a hotplate. Singh and Gundimeda (2014) found that in Indian households the highest energy efficient fuel for cooking purposes is liquefied petroleum gas (LPG). The impact of bioenergy use on rural households, environment and natural resource use has been partly addressed for the developing countries by Djanibekov et al. (2016). Wenhold et al. (2007) provided an overview of the interactions between agriculture using residential land, irrigation water and household food security for South African countries.

As an integrated global model addressing the interactions between water, energy and food at end-use level at a household scale is lacking, this study is aimed at developing one. This system dynamics-based model is developed using a bottom-up approach. The model captures the impact of user behaviour, family size, income, diet, appliances efficiency and seasonal variability on water, energy and food consumption. The disaggregation of water, energy and food into end-uses in the model and their behaviour may help to establish the best practice of management and also to identify areas for improvement (i.e., reduction of consumption).

In this paper, the structure of the developed WEF model is presented with the related mathematical relations. Then, the model assumptions, applications and the required input variables are presented. A brief description about the case study used in the WEF model is described. Then, the sensitivity of model estimations is analysed and its validity tested using Monte Carlo technique. The model results are then compared with the historical data. Finally, the developed model has been applied to investigate the impacts of Global Scenario Group (GSG) scenarios.

2 MODEL DEVELOPMENT

Figure 1 shows the structure of the developed dynamic simulation model for water, energy and food at a household scale. A bottom-up approach was used to develop the model, comprising the interactions between water, energy and food at end-use level. This approach has become very common for modelling sustainable livelihood issues at a household, city and national scales (Biggs et al., 2015). This approach helps to understand the contribution of each end-use in the total consumption. Furthermore, it is the only option to investigate the impact of new interventions and technologies on consumption (Swan and Ugursal, 2009). An end-use based model can identify the end-use with highest resource consumption. Therefore, the proposed model can support the development of retrofitting programs and prioritisation schemes for resource efficient devices.

The key variables of this model are family size, appliances efficiency and the impact of seasonal variability (the duration of winter and summer season) on water, energy and food consumption. Another key variable is the impact of household income (i.e., low, medium and high) on water, energy and food consumption (Figure 1). Many aspects of water, energy and food are addressed in this model, such as the generated wastewater and food waste from a household (Figure 1). The model also calculates the consumption of individual end-use of water, energy and food.

The model components have over 300 variables in total and a simplified version of the model components is presented in Figure 1. The values of all input variables and parameters into the model depend on the trend and pattern of water, energy and food end-uses for the particular region. The detailed explanation of these variables and the mathematical equations which describe the relationships between water, energy and food are explained in Sections 2.1 to 2.6.

System dynamics modelling has been used to model environmental and water systems at various scales (Simonovic, 2002; Stave, 2003; Kojiri et al., 2008; Khan et al., 2009; Qi and Chang, 2011; Mereu et al., 2016). This particular model has been coded using SIMILE modelling environment. SIMILE is a system dynamics modelling software that is used for modelling the interactions between various system components and capturing the changes in this system behaviour over time. SIMILE is selected for its ability to host sub-models and simplify the complex process of interactions between the variables (Vanclay, 2014). The causal-loops between various model components are shown in Figure 2.

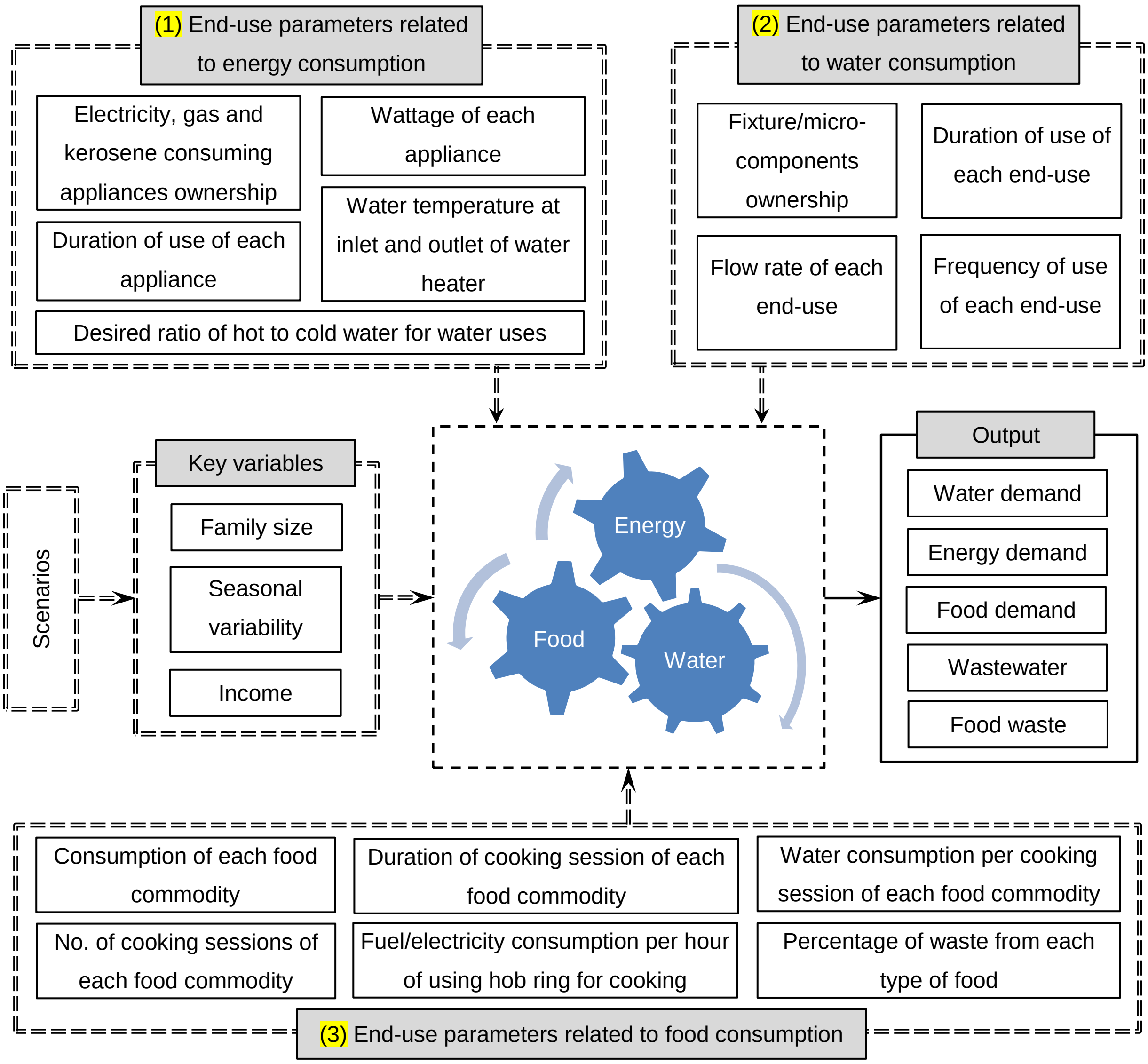


Figure 1 The structure of the water-energy-food model at a household scale

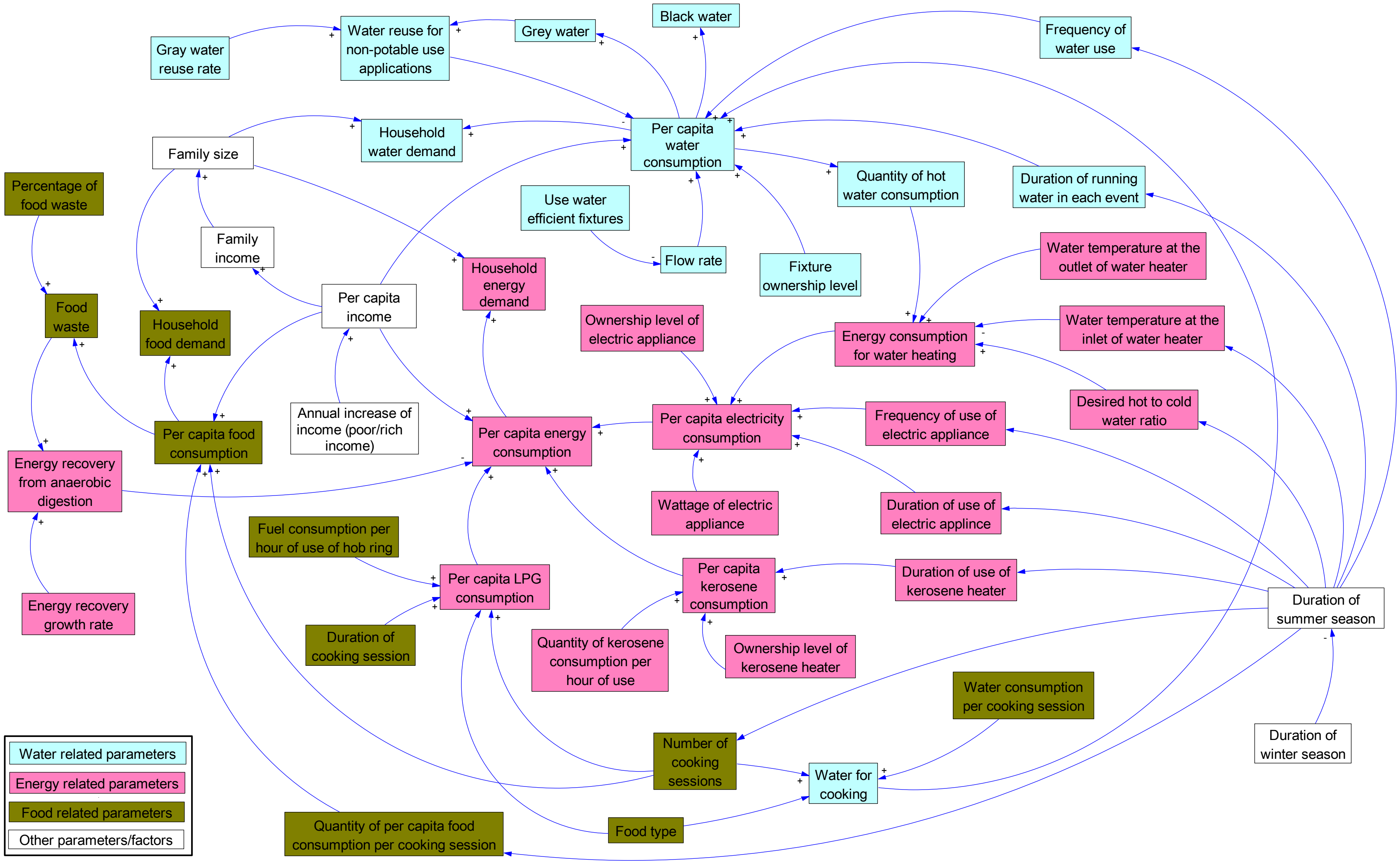


Figure 2 Relationship between water-energy-food parameters and external drivers at a household scale

Within the developed model, stocks represent the accumulated change of a system component (e.g., family size and percentage of each income group: low, medium and high). Flows represent the amount of increase or decrease in the family size and each income group. The factors that affect the system are represented as convertors, such as duration of winter and summer season, variation in the size of each income group, and the parameters that impact water, energy and food end-uses (Section 2.1 to 2.5).

2.1 Modelling of household water consumption

Within the water, energy and food model, household water consumption is disaggregated into various end-uses: showering, bathing, hand wash basin tap use, toilet flushing, dishwashing, clothes washing, cooking, house floor washing, vehicle washing, garden watering, and swimming pool. The model captures the influence of human behaviour for water end-uses, through involving the parameters of water end-use into the model. For example, the frequency of use and the duration of water run during each event of water use are included (components no. 2 in Figure 1). The model involves also the flow rate of water end-use (efficiency of water use fixtures) and the ownership level of water use fixtures and appliances (i.e., clothes washer, dishwasher and bathtub). Using these parameters in Equation 1, the quantity of water consumption of each water end-use (showering, tap use, manual dishwashing, cooking, house floor washing, vehicle washing and garden watering) can be calculated. Equation 2 has been used to quantify water consumption for clothes washing, toilet flushing and bath. The model also calculates black and grey water collected from a household as shown in Figure 3, using Equation 3 and Equation 4.

$$We_i = Fe_i \times De_i \times Re_i \qquad \text{Equation 1}$$

$$We_i = Fe_i \times Ve_i \qquad \text{Equation 2}$$

where:

$We_i =$ daily per capita average consumption for water end-use i (l/p/d),
$Fe_i =$ daily per capita average frequency of water end-use i (number of events/p/d),
$De_i =$ duration of water run during each event of water end-use i (min/event),
$Re_i =$ average flow rate of water end-use i (l/min), and
$Ve_i =$ quantity of water consumption during each event of water end-use i (l/event).

$$GW = WW_b + WW_{sh} + WW_{hw} + WW_{cw} \qquad \text{Equation 3}$$

$$BW = WW_{dw} + WW_c + WW_{tf} + WW_{fw} + WW_{vw} \qquad \text{Equation 4}$$

where: GW=grey water, b=bathing, sh=showering, hw=hand wash basin tap use, cw= clothes washing, BW=black water, dw=dishwashing, c=cooking, tf=toilet flushing, fw, house floor washing, vw=vehicle washing.

Figure 3 shows the interactions between water, energy and food end-uses at a household scale. The direction of an arrow shows water or energy consumption associated with each end-use. These interactions are addressed in the developed model. For instance, the energy consumption for water heating, water for space cooling (i.e., evaporative air-cooler), wet appliances (i.e., water pump, dishwasher, clothes washer), water and energy use for food preparation and energy for food preservation.

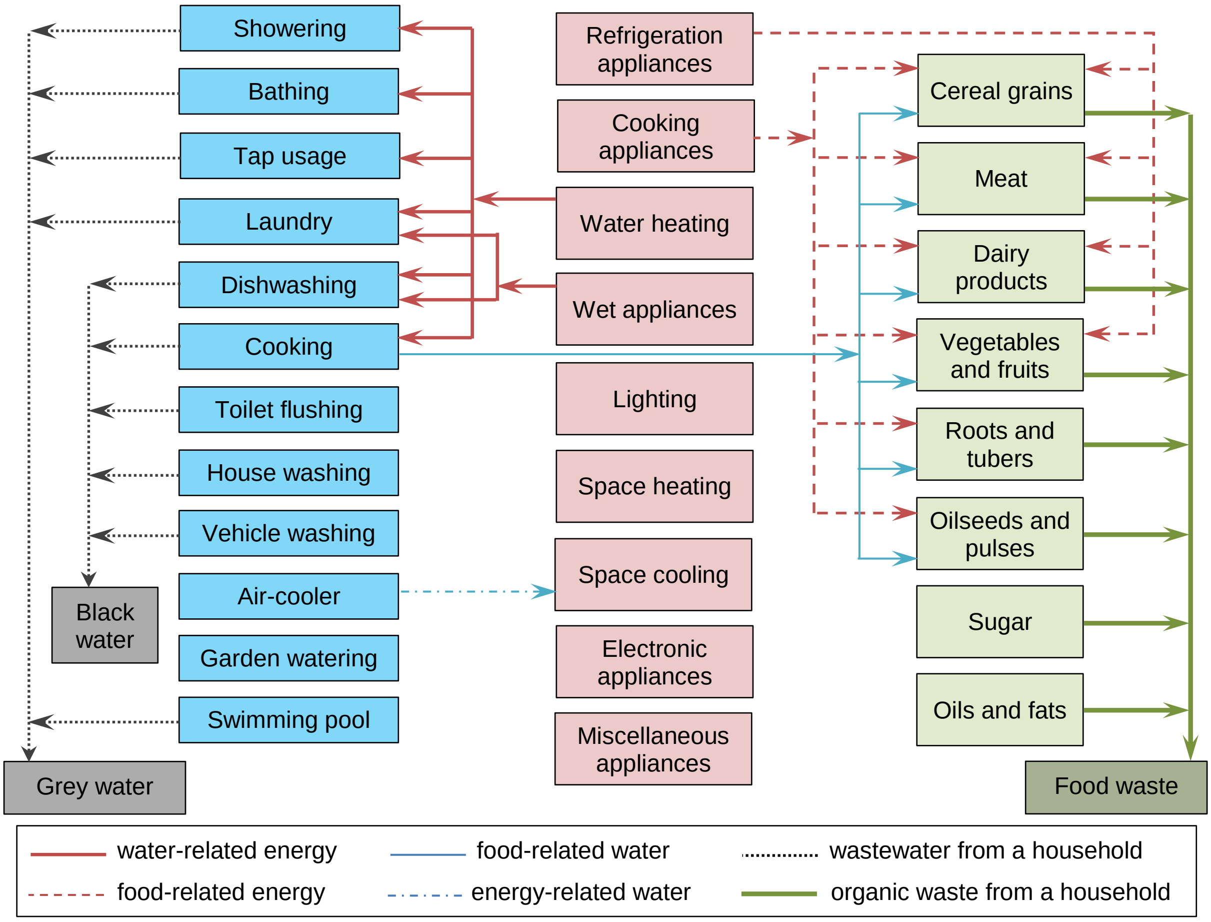


Figure 3 Modelling the interactions between water, energy and food end-uses at a household scale

2.2 Modelling of household energy consumption

The household energy consumption (i.e., electricity, kerosene and LPG) is divided into several end-uses: space heating, water heating, lighting, and refrigeration, wet, electronic, cooking and miscellaneous appliances. Each energy end-use comprises different types of appliances, with the same purpose of use as listed in Table 1. The model involves the appliances presented in this table. The calculation of energy consumption in the developed model for water heating and other appliances is explained in Section 2.2.1 to 2.2.3.

Table 1 Summary of energy end-uses and the related appliances

Energy end-use	Appliances
Space heating	Air-conditioner, electrical heater, kerosene heater, gas heater
Space cooling	Air-conditioner, evaporative air-cooler, fan
Lighting	Spot lights, tube lights
Wet appliances	Water pump, dishwasher, clothes washer
Refrigeration appliances	Chest-freezer, fridge-freezer
Electronic appliances	TV, radio, computer, video record, CD/DVD player, Video games
Miscellaneous appliances	Hair dryer, vacuum cleaner, sewing machine, iron
Cooking appliances	Electrical hob, electrical oven, electrical kettle, microwave oven, toaster, gas oven, gas hob

2.2.1 Energy consumption for water heating

Different types of energy (e.g., electricity, kerosene, and LPG) can be used for household water heating for various uses (i.e., bathing, showering, hand washing basin, laundry, dishwashing, and cooking). The amount of energy consumed for water heating depends on the household composition, inflow and outflow water temperature and fuel type (Aguilar et al., 2005). Another factor is the wattage and efficiency of a water heater (Isaacs et al., 2004). Additionally, energy consumption for water heating may vary with the seasons and climate (Goldner, 1994). Energy consumption for daily water heating can be calculated using a specific heat formula (Equation 5) (Gettys et al., 1989) as given below.

$$E_h = Q_h \times \rho \times S \times (T_{out} - T_{in}) \,/\, 3600 \qquad \text{Equation 5}$$

where:

E_h = daily per capita energy consumption for water heating (kWh/p/d),
Q_h = daily quantity of hot water consumption per capita (m^3/p/d),
ρ = density of water (1000 kg/m^3),
S = specific heat capacity of water = 4.186 kJ/kg ºC,
T_{out} = water temperature at the heater outlet (ºC),
T_{in} = water temperature at the heater inlet (ºC), and
3600 = conversion factor (from kJ to kWh).

Swan (2010) assumed that the delivered water temperature, T_{out}, is 55 ºC and T_{in} is equal to the annual average soil temperature. In order to achieve the preferred tap water temperature (40ºC), it is assumed that 50% of the water used requires heating (i.e., for bathing, showering, taps, dishwashing, laundry and cooking) (Kenway et al., 2008; Fidar, 2010). For the case study in this paper, the same proportion has been assumed for each indoor end-use requires heating to calculate the average per capita hot water consumption. The average temperature of water supply (T_{in}) for the case study is approximately 12 ºC during the cold season (Duhok Directorate of Seismology and Meteorology, 2015). The average water temperature at the outlet of heater (T_{out}) is taken as 62ºC, based on the survey findings. Using the quantity of per capita hot water consumption and Equation 5, the per capita electricity consumption for water heating can be calculated. The model is flexible to accommodate any hot to cold water ratio (components no. 1 in Figure 1) considering various climatic conditions in different regions of the world.

2.2.2 Energy consumption of electric appliances

To calculate the energy consumption of electric appliances, the energy consumption of each appliance is assumed to remain constant throughout its entire operating hours. The energy consumption of each appliance in use in a household is modelled as a function of ownership level (e.g., number of air-conditioners in use in a household), duration of use and wattage (components no. 1 in Figure 1). Using these parameters and Equation 6, the energy consumption of each appliance presented in Table 1 can be calculated as below.

$$Ea_i = Na_i \times Da_i \times Wa_i \qquad \text{Equation 6}$$

where:

Ea_i= daily per capita average energy consumption of appliance i (kWh/p/d),
Na_i= average ownership level of appliance i per household,
Da_i= daily per capita average duration of use of appliance i (hrs/p/d), and
Wa_i= average wattage of appliance i (Watt),

In the developed WEF model, wattage values for appliances in Table 1 are based on the survey findings.

2.2.3 Kerosene and LPG consumption

In addition to the electricity consumption, the WEF model calculates household consumption for other types of energy uses, such as kerosene and LPG. Equation 7 is used to calculate per capita kerosene and LPG consumption for space heating. The energy consumption for food preparation is explained in Section 2.3.2.

$$\mathrm{E}_s = N_s \times D_s \times Q_s \qquad \text{Equation 7}$$

where:

E_s = daily per capita average kerosene/LPG consumption for space heating (l/p/d),
N_s = average number of kerosene/LPG heaters in use in a household,
D_s = daily per capita average duration of use of kerosene/LPG heater (hrs/p/d), and
Q_s = quantity of kerosene/LPG consumption by each heater per hour (l/heater/hr).

2.3 Modelling of household food consumption

Household food consumption is disaggregated into several groups: cereal grains, meat, dairy products, vegetables and fruits, roots and tubers, oilseeds and pulses, oils and fats, and sugar. Each food group comprises various commodities as shown in Table 2. The food commodities presented in this table are included in the WEF model. The daily per capita consumption of each of these food commodities is modelled as a function of the number of cooking sessions per day and the quantity of food consumed per cooking session (components no. 3 in Figure 1) as shown in Equation 8.

Table 2 Summary of food groups and related food commodities

Food groups	Commodity
Cereal grains and products	Wheat flour, rice, burgul & jareesh, buns, cake, biscuits, macaroni & vermicelli
Meat	Chicken & turkey, sheep & goat, bovine, fish & seafood
Dairy products	Yogurt, cheese, egg, milk, butter
Roots and tubers	Potato, onion, carrots, garlic, radish
Vegetables	Tomato, cucumber, aubergine, courgette, okra, lettuce, sweet pepper, celery
Fruits	Water melon, orange, apple, melon, grape, pumpkin, banana
Oilseeds and pulses	Bean, chick pea, lentil
Oils and fats	Vegetable oils, animal fats
Sugar	Sugar

* Milk and oil consumption is modelled in l/p/d

$$F_i = (Nc_i/7) \times Fc_i \qquad \text{Equation 8}$$

where:

F_i = daily per capita consumption of food commodity i (g/p/d),

Nc_i = number of cooking sessions of food commodity i per week (cs/w), and

Fc_i = average quantity of per capita consumption of food commodity i per cooking session (g/p/cs).

In order to calculate the energy and water consumption for food preparation (Figure 3), the model included some other parameters, such as, the quantity of water and energy consumption per cooking session of each food commodity (components no. 3 in Figure 1). The calculation of water and energy consumption for food preparation and generated food waste is explained in the following Sections (2.3.1 to 2.3.3).

2.3.1 Water use for food preparation

The quantity of water consumption for food preparation is modelled as a function of number of cooking sessions per week and water consumption per cooking session (components no. 3 in Figure 1). The model requires these parameters for each food commodity presented in Table 2. Using these parameters in Equation 9, the daily per capita water consumption for cooking each type of food can be calculated.

$$W_i = (Nc_i/7) \times Wc_i \qquad \text{Equation 9}$$

where:

W_i = daily per capita average water consumption to prepare food commodity i (l/p/d),

Nc_i = average number of cooking sessions of food commodity i per week (cs/w), and

Wc_i = per capita average water consumption in each session of washing and cooking food commodity i (l/p/cs).

2.3.2 Energy use for food preparation

The required parameters to calculate the energy consumption for food preparation are the duration of cooking session and fuel consumption per hour for using a hob ring (components no. 3 in Figure 1). Using these parameters for each food commodity (Table 2) in Equation 10, the energy consumption for food preparation can be calculated in the WEF model. In order to calculate the energy use for food preparation, the size of the hob ring used for cooking every type of food is assumed to be the same in all households.

$$E_i = (Nc_i/7) \times (Dc_i/60) \times E_h \qquad \text{Equation 10}$$

where:

E_i = daily average fuel consumption to prepare the food commodity i (l/d).

Dc_i = duration of cooking session of the food commodity i (min/cs) , and

E_h = fuel consumption per hour of using hob ring for cooking (l/hr).

2.3.3 Food waste from household

In each step of the food supply chain (production, processing, distribution and consumption), the percentage of food waste for each type of food is estimated by FAO (2011), for different world regions. Table 3 shows the percentages of food waste for each type of food during the consumption step of food supply chain in different regions. The table shows that food waste at a consumption step in Sub-Saharan Africa, South and Southeast Asia is very low, compared to the other regions of the world. Using these percentages in Equation 11, the quantity of food waste from a household can be calculated in the WEF model. The calculated food waste is influenced by the quantity of per capita food consumption, which is a function of household income and seasonal variability. The values in Table 3 can be used in the developed model to quantify food waste in the regions of interest.

Table 3 Percentage of waste from various types of food within the consumption step of food supply chain (FAO, 2011)

Region	Cereal grains	Meat	Fish and sea food	Dairy products	Roots & tubers	Vegetable & fruits	Oilseeds & pulses
Europe including Russia	25	11	11	7	17	19	4
North America and Oceania	27	11	33	15	30	28	4
Industrialised Asia	20	8	8	5	10	15	4
Sub-Saharan Africa	1	2	2	0.1	2	5	1
North Africa, west and central Asia	12	8	4	2	6	12	2
South and Southeast Asia	3	4	2	1	3	7	1
Latin America	10	6	4	4	4	10	2

$$FW_i = PFW_i \times F_i \qquad \text{Equation 11}$$

where:

FW_i = quantity of waste from food commodity i (g/p/d), and

PFW_i = percentage of waste from food commodity i (%).

2.4 Impact of income on water, energy and food

Income and wealth can be a major factor influencing per capita water, energy and food consumption. Kriström (2008) stated that income is the key driver for household energy consumption, reflecting increased affordability with an increase in income. Per capita water consumption also increases with an increase in household income (Willis et al., 2013). Although, other factors, such as occupant's age, education level and house size can have a marginal impact on resources consumption (Hewitt and Hanemann, 1995; Grafton et al., 2011), the major consumption influencing factors are household income and seasonal variability (Anker-Nilssen, 2003; Okutu, 2012; Palmer et al., 2013). Therefore, the developed model investigates the impact of these factors on water, energy and food consumption.

The households are divided into three income groups (i.e., low, medium and high) based on the classification of CSO and KRSO (2012) (Table 4). Based on this classification, the parameters relating to water, energy and food end-uses (components no. 1, 2 and 3 in Figure 1), which are presented in Section 2.1 to 2.3, are classified and defined in the model for each income group, individually. The values assigned to these parameters are derived from the two surveys conducted as discussed in Section 4.2. The input parameter values to quantify water demand in the model can be found in Hussien et al. (2016). Consequently, the model estimates water, energy and food consumption for low, medium and high income households.

Table 4 Income groups classification for Iraq (CSO and KRSO, 2012)

	Income range in each income group in Iraqi Dinar (ID)		
	Low	Medium	High
Per household	$<1\times10^6$	1×10^6 - 2×10^6	$>2\times10^6$
Per capita	$<15\times10^4$	15×10^4 - 30×10^4	$>30\times10^4$

2.5 Impact of seasonal variability on water, energy and food

The household energy consumption varies seasonally due to changes in the energy requirements for space heating and cooling (Lam et al., 2008). Svehla (2011) showed a significant seasonal variation in refrigeration, cooking and the use of some other appliances. Most studies assumed that indoor water consumption, except for evaporative air-cooling, remains unchanged throughout the year (Rathnayaka et al., 2015). However, in addition to garden watering, swimming pool and evaporative air-cooling, indoor water end-uses do vary seasonally. An example is showering, which increases in summer (Rathnayaka et al., 2015).

The WEF model captures the impact of seasonal variability on the consumption of water, energy and food at a household scale. In order to achieve this, modifications were made for different end-uses.

To estimate water consumption during the summer season, evaporative air-cooler end-use is added to the other water end-uses which are presented in Section 2.1. Consequently, the annual per capita average water consumption can be calculated using Equation 12.

$$TW = d_w \times \sum_{i=1}^{n} [We_i]_w + d_s \times \sum_{i=1}^{m} [We_i]_s \qquad \text{Equation 12}$$

where:

$TW=$ annual per capita total water consumption (l/p/year),

$[We_i]_w$= daily per capita water end-use i during winter season (l/p/d),

$[We_i]_s$= daily per capita water end-use i during summer season (l/p/d),

d_w= duration of winter season (d), and

d_s= duration of summer season (= *365* – *d*$_w$) (d).

In terms of energy consumption during the summer season in the WEF model, the space heating appliances are replaced with space cooling appliances (i.e., fan, evaporative air-cooler and air-conditioner) (Table 1). Equation 13 is used in the WEF model to calculate the annual per capita energy consumption for each income group.

$$TE = d_w \times \sum_{i=1}^{n} [Ee_i]_w + d_s \times \sum_{i=1}^{m} [Ee_i]_s \qquad \text{Equation 13}$$

where:

TE= annual per capita total energy consumption (kWh/p/year),

$[Ee_i]_w$= daily per capita energy end-use i during winter season (kWh/p/d), and

$[Ee_i]_s$= daily per capita energy end-use i during summer season (kWh/p/d).

Similarly to Equation 12 for water and Equation 13 for energy, the model calculates the seasonal variability of food consumption and also the water and energy use for food preparation. This is achieved by using the parameters of each food commodity for each income group during winter and summer seasons. The survey data analysis indicates that in general terms WEF increases with the household income. The water consumption is 270 l/p/d in winter and increases to 334 l/p/d in summer. The energy consumption increases in winter (15.5 kWh/p/d) compared to that in summer (12.1 kWh/p/d). Food consumption broadly remains same in winter and summer. The parameters influencing consumption and their respective values for different seasons and income groups are available in supplementary material as given in Table A1 to A3.

2.6 Family size

The analysis of our conducted survey (Hussien et al., 2016) strongly suggests that Duhok family size is influenced by family income. Therefore, in the WEF model, the impact of a family size (*FS*) is addressed as a function of increase/decrease in the family income (Equation 14).

$$FS = \sum_{j=1}^{3} P_j \times FS_j \qquad \text{Equation 14}$$

where:

P_j= percentage of households in income group *j (j=low, medium and high*), and

FS_j= average family size of the income group j. FS_j values are constant as derived from the conducted survey and are shown in Table 5.

Table 5 Impact of income on average family size in Duhok, Iraq

	Low income	Medium income	High income
Average family size	4.82	7.10	8.45

3 MODEL ASSUMPTIONS

The key assumptions include:

1) Although, some electric appliances operate on different power ratings, the model reports an average energy consumption of each appliance throughout its entire operating hours rather than capturing short time scale variability.
2) Electricity is the main source for water heating at a household level. This is based on the household survey findings.
3) The hot to cold water ratio is assumed to be 1:1 for each end-use that required hot water in Duhok households. However, the model is flexible to accommodate any hot to cold water ratio considering various climatic conditions in different regions of the world.
4) The average temperature of water supply (T_{in}) is approximately 12 ºC during the cold season (Duhok Directorate of Seismology and Meteorology, 2015). The average water temperature at the outlet of heater (T_{out}) is taken as 62ºC, based on the survey findings.
5) The size of hob ring used for cooking every type of food is the same in all income households.

6) The capacity of LPG cylinder is assumed as 26.2 l. This is the predominant cylinder size in Iraq (Kurdistan Ministry of Natural Resources, 2014).
7) There is no leakage in the household.
8) The survey results indicated that bath and swimming pool ownership is very low. It is assumed as zero.

4 MODEL APPLICATION

The developed WEF model has various applications that can support appropriate policy formation and analyse future consumption related implications:

1) Specify the highest end-use of water/energy in terms of consumption. This can assist to find the suitable strategy to reduce that end-use and the related waste.
2) Estimate the consumption of each food commodity at a household scale, which can help to plan for the future land-use for agricultural crops.
3) Evaluate the impact of new technologies and efficiency enhancement programs on water (e.g., use recycled grey water for non-potable applications), energy (e.g., use anaerobic digestion for energy recovery from food waste) and food when they are applied to a household.
4) Enable the decision-makers and stakeholders to compare between different scenarios and their respective resource requirements to find the preferable management policy.

4.1 Model input parameters

A summary of model input parameters is given in Table 6. Each input parameter, labelled with an asterisk (*), could have six different values depending on weather (summer or winter) and household income (low, medium and high). The input parameter values for water, energy and food demand estimation are provided as supplementary material for this paper. The values for these parameters have been derived from a detailed survey conducted for the chosen case study city, Duhok, Iraq, which is described in the following section. The non-survey-based data used in the WEF model and their spatial resolution are provided in Table 7.

Table 6 Summary of model input parameters

Input parameters	Key driver/end-use
Average family size of low, medium and high income households (FS_j)	Key drivers
Proportion of low, medium and high income households (P_j)	
Duration of summer and winter seasons	
Frequency of use of water end-use (Fe_i) *	Showering, hand wash basin tap use, manual dishwashing, cooking, house floor washing, vehicle washing and garden watering
Duration of use of water end-use (De_i) *	
Flow rate of water end-use (Re_i) *	
Frequency of use of water end-use (Fe_i) *	Bathing, toiler flushing and clothes washing
Quantity of water consumption during each event of water end-use (Ve_i) *	
Ownership level of electric appliance (Na_i)	Air-conditioner, electric heater, evaporative air-cooler, fan, spot lights, tube lights, water pump, dishwasher, clothes washer, chest-freezer, fridge-freezer, TV, radio, computer, video record, CD/DVD player, Video game, hair dryer, vacuum cleaner, sewing machine, iron, electric hob, oven, kettle, microwave, and toaster
Duration of use of electric appliance (Da_i) *	
Wattage of electric appliance (Wa_i)	
Ownership level of kerosene and gas use appliance (N_d)	Kerosene heater, kerosene hob, gas heater, gas hob and gas oven
Duration of use of kerosene and gas use appliance (D_s) *	
Quantity of kerosene/gas consumption by the appliance (Q_s)	
Water temperature at inlet of water heater (T_{in})	Water heating uses
Water temperature at outlet of water heater (T_{out})	
Desired ratio of hot to cold water for water uses	
Number of cooking sessions of a food commodity (Nc_i) *	Wheat flour, burgle & jareesh, buns, cake, biscuits, macaroni & vermicelli, chicken & turkey, sheep & goat, bovine, fish & sea food, yogurt, cheese, egg, milk, butter, potato, onion, carrots, garlic, reddish, tomato, cucumber, aubergine, courgette, okra, lettuce, sweet pepper, celery, water melon, orange, apple, melon, grape, pumpkin, banana, bean, chick pea, lentils, vegetables oils, animal fats and sugar.
Quantity of consumption of the food commodity per cooking session (Fc_i) *	
Average water consumption per cooking session of the food commodity (Wc_i) *	
Duration of cooking session of the food commodity (Dc_i) *	
Fuel consumption per hour of using hob ring for cooking (E_h) *	
Percentage of waste of food commodity	

Table 7 Summary of non-survey based data

Parameters	Unit	Value	Spatial resolution	Reference
Water temperature at inlet of water heater	°C	12 ºC during the cold season	Local	Duhok Directorate of Seismology and Meteorology (2015)
Classification of household income groups	ID	Table 4	National	CSO and KRSO (2012)
Capacity of LPG cylinder	l	26.2	National	Kurdistan Ministry of Natural Resources (2014)
Waste from each type of food	%	Table 3	Regional	FAO (2011)
Average wattage of spot lights	Watt	40	National	Iraqi Ministry of Electricity (2010)
Average wattage of tube lights	Watt	60	National	Iraqi Ministry of Electricity (2010)

* l=litres of LPG , ID=Iraqi Dinar

4.2 Case study

The developed model was applied using the data collected from the city of Duhok located in the Kurdistan region in Iraq. Duhok has a population of around 295,000 inhabitants with 4.9% fertility rate (CSO and KRSO, 2006). The average family size in Duhok is 6.7 (2.47 child, 2.01 adult female, 1.96 adult male and 0.25 elder) with monthly average family income 1664.9x10^3 ID (CSO and KRSO, 2012). The city has seen considerable urbanisation and changes in land use patterns resulting in additional demand for water, food and energy (Kurdistan Regional Statistics Office (KRSO), 2014).

Energy supply to Duhok households increases annually with a rate of 9% (General Directorate of Duhok Electricity, 2014). Per capita meat consumption has also increased in Duhok households to 24 kg/p/y in 2014 (Kurdistan Ministry of Agriculture and Water Resources, 2014). Due to the increase in Duhok household's consumption for WEF, it is selected as a case study in this paper. A detailed survey on water, energy and food consumption was carried out for representative sample (i.e, 419 households) of the city population during winter and summer season. Further details on the case study site are given in Hussien et al. (2016).

5 MODEL RESULTS

Using the case study of Duhok, the sensitivity of the WEF model estimations to the input parameters is analysed. The model validity is tested using uncertainty assessment analysis. Then the model results are compared with the historical data.

Finally, the WEF model is used to investigate the impact of future scenarios on the household demand for water, energy and food.

5.1 Model sensitivity

In order to calculate the sensitivity of the model output to the input parameters, one-at-a-time analysis method has been used. This method considers the range of variation in input parameters as its standard deviation below and above its average value (i.e., average ± standard deviation) (Hamby, 1995). Then, the change in model output (water and energy demand) is quantified by using the upper and lower value of each input parameter individually, while holding all other input parameters at their base-case value (Cullen and Frey, 1999). This method does not account for interactions between the input parameters (Frey and Patil, 2002; Saltelli and Annoni, 2010), but provides a clear indication how a single parameter influences the overall outcome.

Figure 4 shows the sensitivity of water demand estimation to the input parameters. The highest sensitivity is attributed to the frequency and duration of each session of garden watering. Their contribution to the sensitivity of water demand estimation accounts approximately to ±1.5% of the base-case estimated demand (i.e., the estimated demand when all input parameters set to their mean).

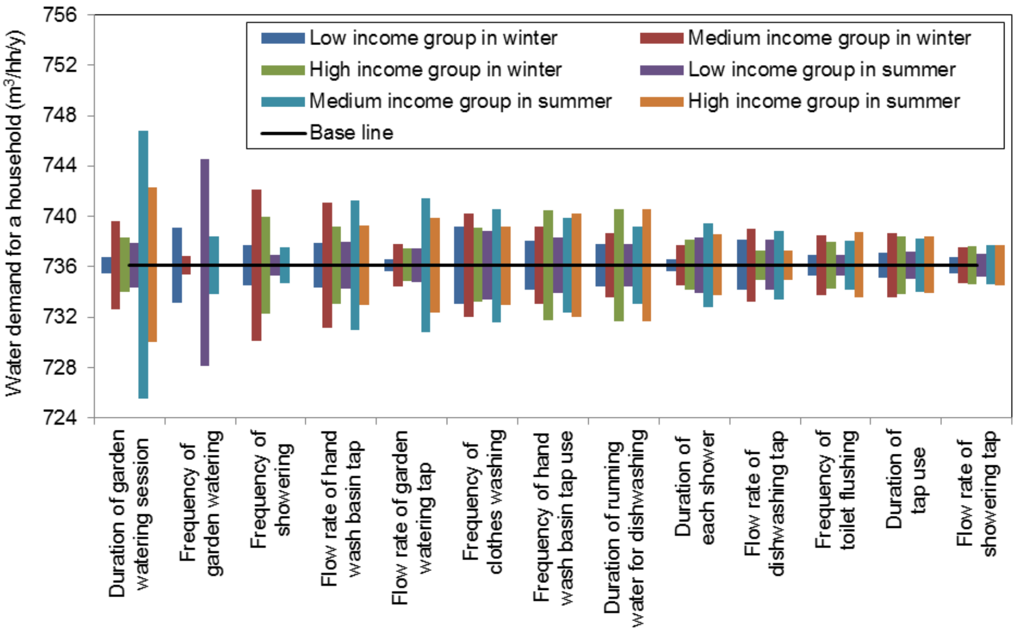


Figure 4 Sensitivity analysis of household water demand estimation to the input parameters

The sensitivity of electricity demand estimation to the model input parameters is shown in Figure 5. It is clear from this figure that the estimation of electricity demand is highly sensitive to the ownership level and the duration of the use of air-conditioners in a household (±4% of the base-case estimated demand). This may be due to the high variation in ownership level (average=1.36, variance=0.98) and the duration of the use of air-conditioners (average=10 hrs/hh/d, variance=7.3 hrs/hh/d) between Duhok households. However, the other input parameters have less impact on the electricity demand estimation (±1% of the base-case estimated demand).

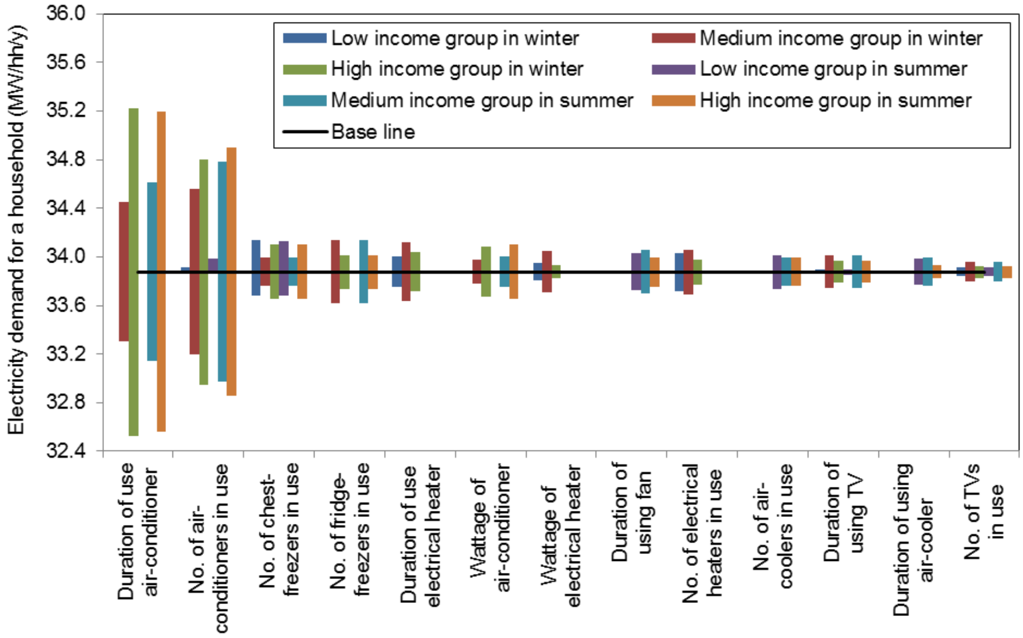
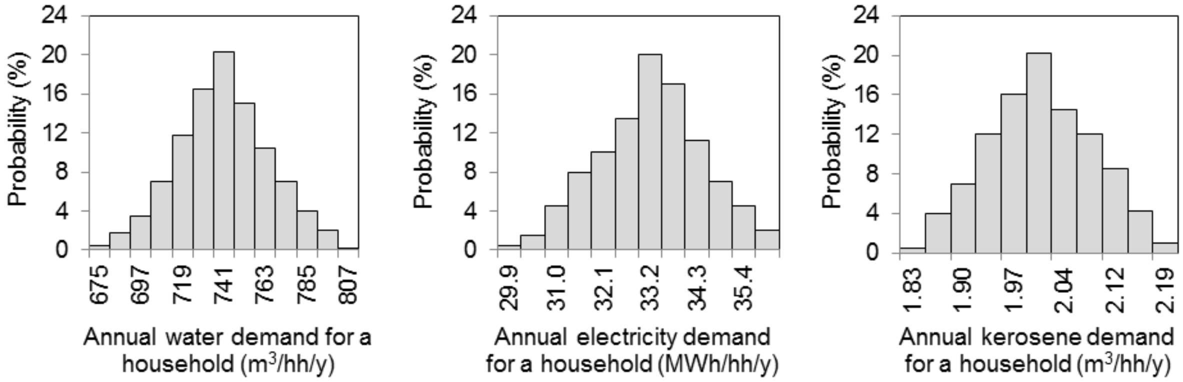


Figure 5 Sensitivity analysis of household electricity demand estimation to the input parameters

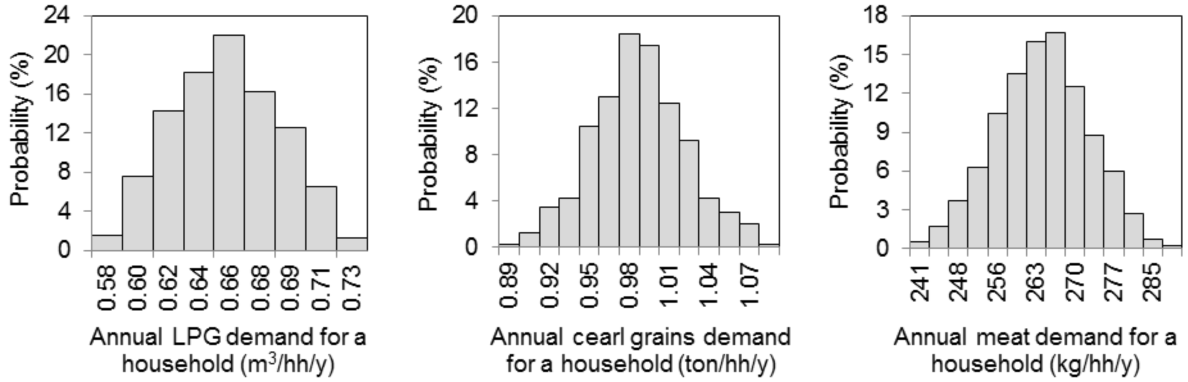
Overall, for the parameters obtained from the survey, the model has shown reasonable predictions. In order to increase confidence in the results, a formal uncertainty assessment was performed as discussed below.

5.2 Uncertainty analysis

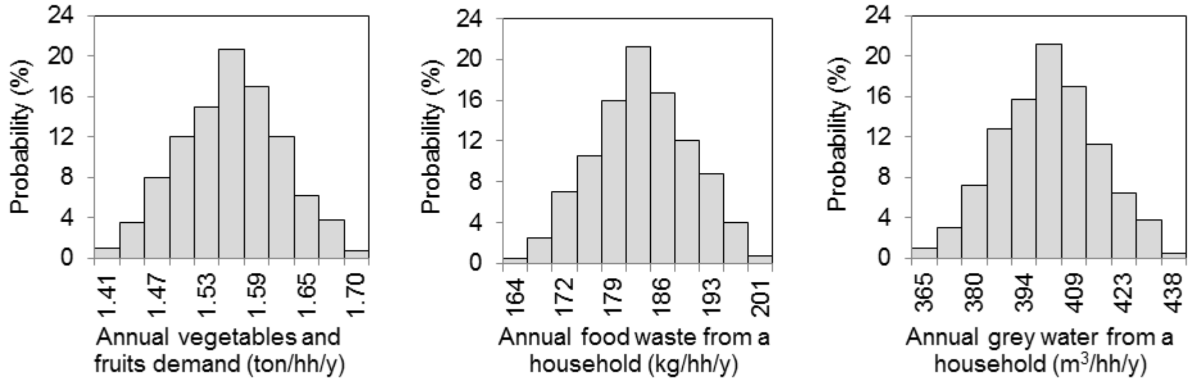
The uncertainty of model output is analysed using the Monte Carlo technique. This technique has been used by Kenway et al. (2013) and Schaffner et al. (2009) to test the uncertainty of their models. For each input parameter into the WEF model, random values are selected from the distribution of possible values for input parameter under consideration. The random values of input parameters are used in the developed model and the expected value of the output is calculated to evaluate the impact of multiple uncertain parameters. The process is repeated for a number of iterations. Then, the probability distribution of the calculated outputs is plotted as shown in Figure 6. The analysis shows that the uncertainty for water demand estimation is lower than that for energy. This is because the relative width (standard deviation/average (Schaffner et al., 2009)) of estimated demand for water (0.03) is less than that for electricity, kerosene and LPG (0.04, 0.04 and 0.05, respectively). The relative width of estimated demand for food types in Figure 6 is less than 0.04.



a. water b. electricity c. kerosene



d. LPG e. cereal grains f. meat



g. vegetables and fruits h. food waste i. grey water

Figure 6 Probability distributions of Monte Carlo simulations

5.3 Comparison of WEF model results with historical data

The results of the developed model are compared against the available historical data which are published in reports or collected from local directorates (KRSO, 2014; COSIT et al., 2010; General Directorate of Duhok Electricity, 2014) in Duhok for the business as usual scenario (i.e., current family size, demographic and household characteristics). The comparison between the model results and the available historical figures for water, energy, food consumption and waste generation is presented in Table 8. The results show that the estimated values of the WEF model are close to the measured historical data. However, the simulation results of food consumption are slightly higher than the historical data. This is probably because the historical data of food consumption in Table 8 are based on daily per capita average calorie intake (2580kcal/p/d) in Iraq, which is less than that in Duhok (2910kcal/p/d) (COSIT et al., 2010).

Table 8 comparison of model results with historical measured data at a household level

Description	Unit	Model results	Historical data	Reference
water consumption in winter	l/hh/d	1816	1896	KRSO (2014)
water consumption in summer	l/hh/d	2238	2298	
energy consumption in winter	kWh/hh/d	102	97	General Directorate of Duhok Electricity (2014)
energy consumption in summer	kWh/hh/d	79	74	
cereal grains consumption	g/hh/d	2702	2620	COSIT et al. (2010)
meat consumption	g/hh/d	728	639	Kurdistan Ministry of Agriculture and Water Resources (2014)
dairy consumption	g/hh/d	605	607	COSIT et al. (2010)
roots and tubers consumption	g/hh/d	933	529	
vegetables consumption	g/hh/d	2888	2396	
fruits consumption	g/hh/d	1416	1175	
oilseeds and pulses consumption	g/hh/d	350	241	
oils and fats consumption	g/hh/d	240	241	
sugar consumption	g/hh/d	505	489	
food waste	g/hh/d	969	1005	Duhok Directorate of the Municipalities (2014)
average family size	no.	7.04	6.7	CSO and KRSO (2012)

To prove the validity of the model results of food consumption, the simulation results of the quantity of daily per capita average food consumption are converted into calories using the conversion factors given by COSIT et al. (2010). These factors are based on FAO (2004) and have been adapted to take into account the specifications of available food commodities in Iraq. The results show that the daily per capita average calorie intake is approximately 2880kcal/p/d in Duhok. The detailed comparison at end-use level is not possible because water, energy and food consumption at micro-level have not been addressed for Duhok households.

5.4 Scenarios analysis

The implications of Global Scenario Group[1] scenarios on water, energy and food demand are investigated in this paper. The scenarios are explained in Table 9.

Table 9 Summary of GSG scenarios (Kemp-Benedict et al., 2002)

Scenario	Definition	Implications
Market force (MF)	the globalized governance, trade liberisation and consumerist values lead to free market behavior.	high growth in population, productivity, economy, GDP and income and also inequality between rich and poor countries, and within each country. The consumption for water, energy and wastes will increase.
Fortress world (FW)	the powerful world forces, faced with a dire systemic crisis, impose an authoritarian order where elites retreat to protected enclaves, leaving impoverished masses outside.	rapid deterioration in environmental conditions, pollution, climate change, water scarce, food insecurity and health crisis with a large socio-economic divide between rich and poor.
Policy reform (PR)	the world establishes the necessary regulatory, economic, social, technological, and legal mechanisms to meet social and environmental sustainability goals, without major changes in the state-centric international order, modern institutional structures, and consumerist values.	achieve internationally recognized goals for poverty reduction, climate change stabilisation, ecosystem preservation, freshwater protection, and pollution control. As a result, greenhouse emissions decline, growth continues in developing countries for two decades as redistribution policies raise incomes of the poorest regions and most impoverished people.
Great transition (GT)	social values move toward internationalism rather than localism and also concerned with environmental conservation, which leads to high growth and development, and service directed change.	increase in wastewater reuse and a decline in fossil fuel energy use and intensive agriculture leading to a reduction in the leakage and water demand.

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[1] http://gsg.org

Numerous studies and assessments have relied on GSG scenarios, such as OECD (2001), WWV (2000) and UNEP (2002). According to GSG, water, energy and food consumption and poor/rich income ratio are assumed to vary from region to region. For the case study located in Iraq, values associated with the Middle East have been used as given in Table 10. The growth rates in this table reflect percentage change in consumption. The model initially used to calculate the base consumption, based on parameter values obtained from the survey. The consumption in each scenario is then calculated by the household WEF model using respective values for poor/rich income ratio in Table 10. The annual demand for water, energy and food has been simulated for 35 years ahead. The time horizon of 35 years is the most often considered timeline in scenarios (Hunt et al., 2012; Ercin and Hoekstra, 2014) and also recommended for socioeconomic planning (Simonovic and Fahmy, 1999).

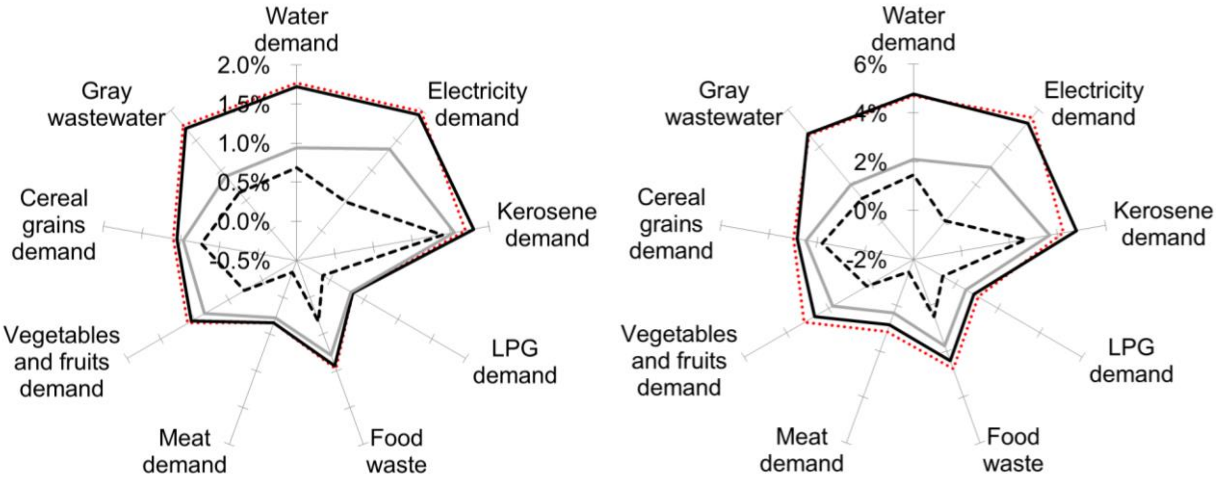
Table 10 Summary of annual growth rate (%) of indicators of GSG scenarios for Middle East region

Indicators	Market force		Policy reform		Fortress world		Great transition	
	2005-2025	2025-2050	2005-2025	2025-2050	2005-2025	2025-2050	2005-2025	2025-2050
Poor/rich income ratio	0.03	0.03	0.2	0.15	-0.1	-0.3	0.6	0.5
Meat consumption	0.7	0.6	0.9	0.7	0.7	0.2	0.9	0.3
Crop consumption	2.1	1.4	2.0	1.2	2.2	1.3	1.9	0.9
Household energy	3.8	3.1	3.0	1.6	3.9	2.4	2.6	0.1
Domestic water	3.4	2.6	1.9	0.6	3.5	2.0	1.8	0.4
Domestic fuel	3.6	2.2	3.1	1.0	3.4	1.6	2.9	-0.4

Figure 7 shows the impact of GSG scenarios on the future demand for water, energy and food and the generated waste. In this figure, the simulated future changes in the household demand are presented as a percentage of the current demand. The results show that within these scenarios, the highest increase in the household demand is attributed to the fortress world scenario. This is mainly due to the increase in high income households which leads to increase the family size.

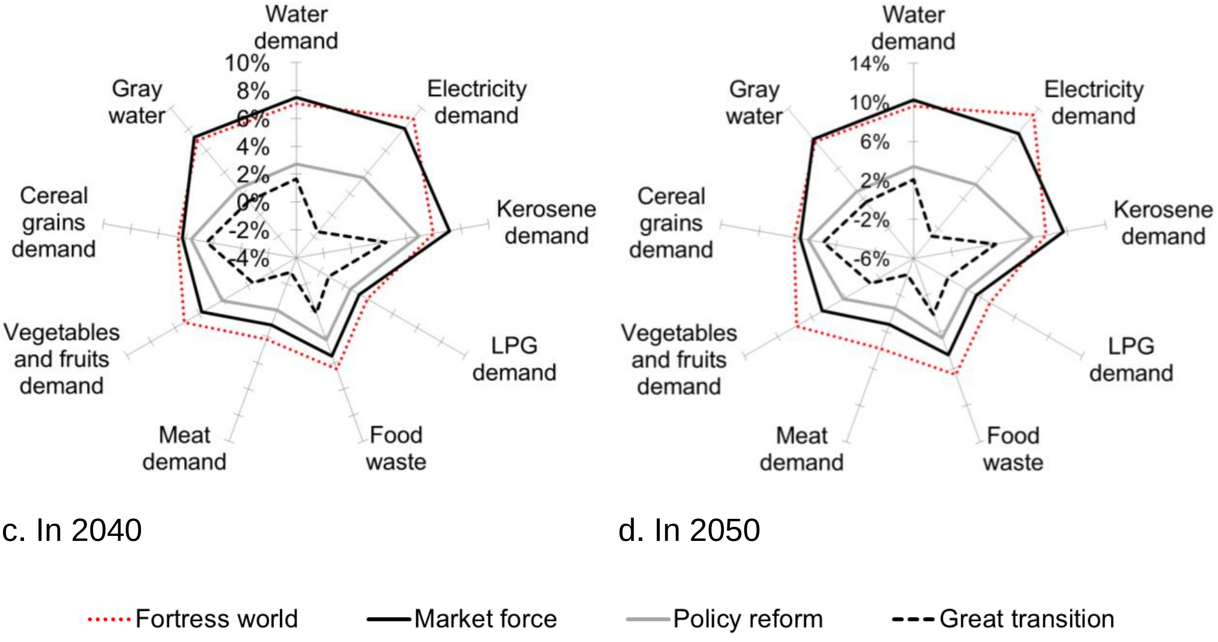
The impact of GSG scenarios on the interactions between water, energy and food is also simulated as shown in Table 11. The results in this table show that the food-related energy in fortress world scenario is higher than the other scenarios. The water-related energy in market force scenario is slightly higher than that in the fortress world scenario. At a household level, the impacts of different scenarios are marginal (Table 11). However, when extrapolated to a city level, noticeable differences and resources implication were observed.

The developed WEF model at a household level can be improved to include the greenhouse gas emissions and the impact of other socioeconomic variables on the consumption. The model can also be expanded to include the demand for other sectors (agricultural, industrial and commercial) in the city. This is to forecast the demand for water, energy and food for the whole city.



a. In 2020

b. In 2030



c. In 2040

d. In 2050

Figure 7 The impact of GSG scenarios on water-energy-food at a household level

Table 11 The impact of GSG scenarios on the interactions between water, energy and food at a household level

Future scenarios	Energy for water (GJ/hh/y)			Energy for food (GJ/hh/y)			Water for food (m^3/hh/y)		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
Business as usual	24.3	24.3	24.3	20.9	20.9	20.9	35.7	35.7	35.7
Market force	25.5	26.2	26.9	21.1	21.2	21.2	36.4	36.7	37.0
Policy reform	24.9	25.1	25.3	21.0	21.0	21.0	36.2	36.3	36.5
Fortress world	25.4	26.0	26.6	21.1	21.3	21.6	36.5	37.0	37.6
Great transition	24.7	24.9	25.1	20.8	20.7	20.5	35.8	35.6	35.5

6 CONCLUSION

The purpose of the current study was to present the structure of a developed integrated model for water, energy and food consumption at a household scale. The developed model addresses the impact of lifestyle change (user behaviour), family size, household income, appliances efficiency and climate change (increase/decrease the duration of summer season) on the future demand for water, energy and food. The availability of the WEF model may assist the decision-makers and stakeholders to investigate nexus problems at a household level and the implications of management policy for water, energy and food. The model can also be expanded to include the demand for water, energy and food and their interactions in the other sectors (agricultural, industrial and commercial) in the city. This is to forecast the demand for water, energy and food for the whole city.

Two seasonal surveys were conducted in 419 households in the city of Duhok, Iraq, to collect data on water, energy and food consumption during the winter and summer seasons. The survey data were used with the developed model to simulate the demand for water, energy and food and the generated food waste and wastewater streams. The model sensitivity to the input parameters is analysed. Additionally, the simulation results were compared with the measured historical data to test the model validity. The model results show a good agreement with the measured historical profiles. The model was applied to investigate the impact of four possible scenarios: market force, fortress world, great transition and policy reform. The results suggest that the fortress world scenario has the highest negative impact on household water, energy and food consumption.

Software, WEF model and data availability

Software name: Simile (i.e., modelling software for scientific research projects in the earth, environmental and life sciences)

Software developer and contact address: Simulistics (a spin-out company from the University of Edinburgh). Address: Simulistics Ltd., 2B Pentland Park, Loanhead, Midlothian, UK. Tel: +44 (0)131 448 2982. Fax: +44 (0)131 448 2982. Email: info@simulistics.com

Software availability and cost: Simile software full version requires licence and can be downloaded at http://www.simulistics.com/simile-version-67-released

Software size: 27 MB

Operating system required for software: 32-bit Windows: Windows 95 or later.

Name of the developed model: WEF model

WEF model developer and contact address: Wa'el A. Hussien, Fayyaz A. Memon and Dragan A. Savic. University of Exeter, Exeter, Devon, UK. E-mail: wahh201@exeter.ac.uk

WEF model data availability: provided as supplementary material

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