

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

Wa'el A. Hussien ^{a, b, *}, Fayyaz A. Memon ^a, Dragan A. Savic ^a

^a Centre for Water Systems, College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, UK

^b Water Resources Engineering, College of Engineering, University of Duhok, Duhok, Iraq

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).

* Corresponding author. E-mail address: wahh201@exeter.ac.uk, wael@uod.ac

30 Households consume considerable quantities of resources (water, food and energy)
31 to meet everyday demand of inhabitants. **The household** is a unit of demand and it
32 can also be the most appropriate unit for influencing consumption practices. A high
33 portion of water, energy and food consumption in the cities can be attributed to
34 household uses. For instance, energy consumption at a household level in Burkina
35 Faso and Duhok in Iraq accounts approximately 75% (Hermann et al., 2012) and
36 80% (General Directorate of Duhok Electricity, 2014) of the total city consumption,
37 respectively. Most studies investigated the Nexus at the national and international
38 scale, while limited attention has been paid to the interactions between water, energy
39 and food at a household scale (Djanibekov et al., 2016; Endo et al., 2015; Loring et
40 al., 2013). **A single element of the nexus** has been addressed in some studies. For
41 example, Cominola et al. (2016) and Daioglou et al. (2012) modelled domestic water
42 demand at end-use level. Sarker and Gato-Trinidad (2015) developed a model for
43 household water demand estimation in Yarra Valley Water, Australia at end-use
44 level. However, their model did not include garden watering end-use. Additionally,
45 energy consumption and associated emissions from a household in Delhi is
46 modelled by Kadian et al. (2007). They considered the impact of income and family
47 size on energy consumption. Aydinalp et al. (2002) modelled domestic energy
48 consumption at end-use level.

49 The interactions between water and energy at a household level have not been
50 addressed very intensively (Kenway et al., 2013). For example, Cheng (2002)
51 analysed water-related energy in residential buildings in Taiwan. They found that
52 88% of water-related energy use is attributed to water heating and household water
53 pumping, while the rest is used for water treatment, water supply and wastewater
54 treatment. Arpke and Hutzler (2006) modelled four household types and showed that
55 97% of water-related energy is attributed to water heating. Based on this model,
56 Flower (2009) simulated water heating-related energy in Victoria, Australia using
57 electricity and gas heater. Kenway et al. (2013) developed a model to investigate the
58 energy use for household water heating in Brisbane, Australia, without considering
59 the impact of **household characteristics**. They found that the household is the key
60 driver for energy consumption and associated greenhouse gas emissions in the city.

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

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

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

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

100 **2 MODEL DEVELOPMENT**

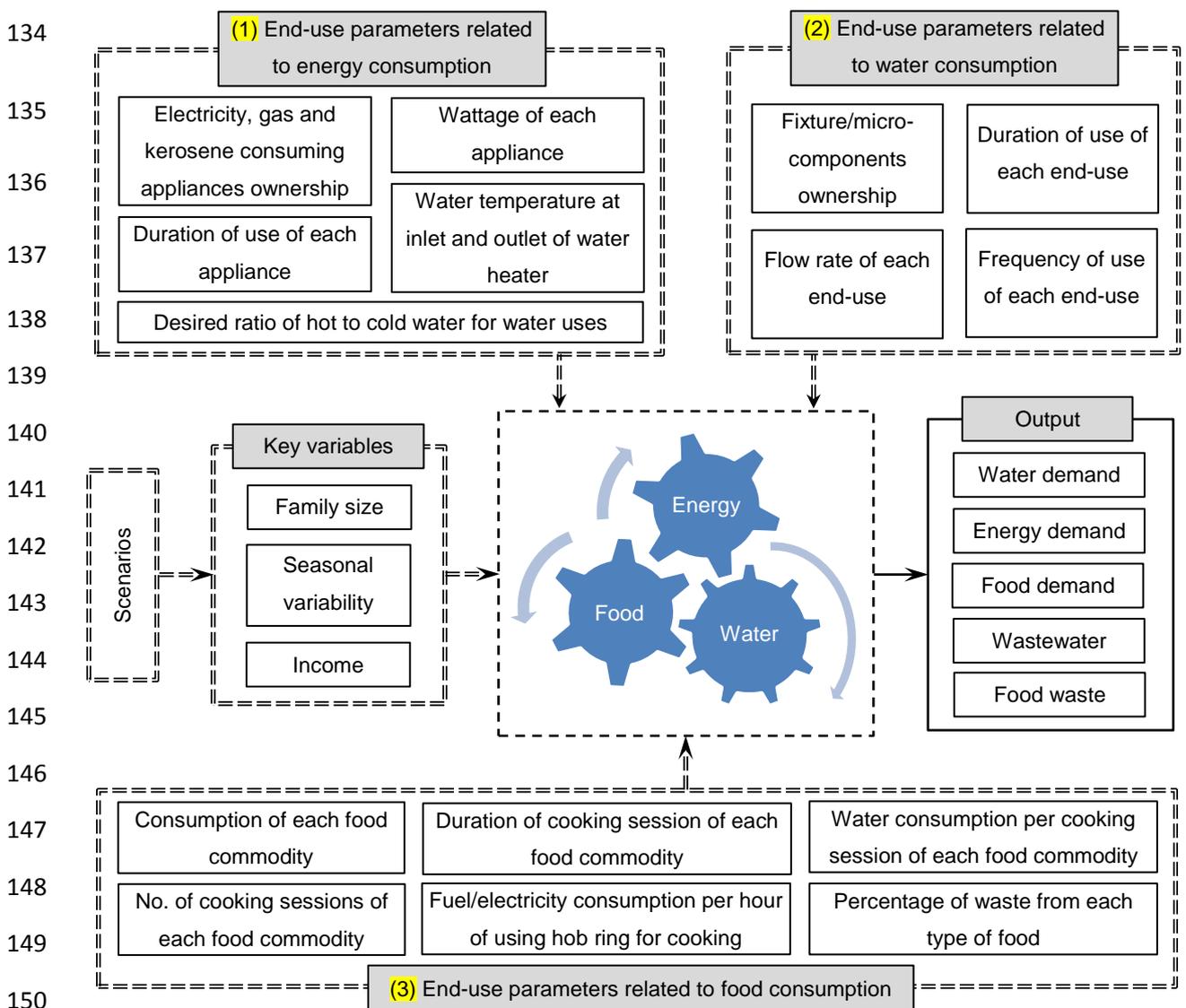
101 Figure 1 shows the structure of the developed dynamic simulation model for water,
102 energy and food at a household scale. A bottom-up approach was used to develop
103 the model, comprising the interactions between water, energy and food at end-use
104 level. This approach has become very common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

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

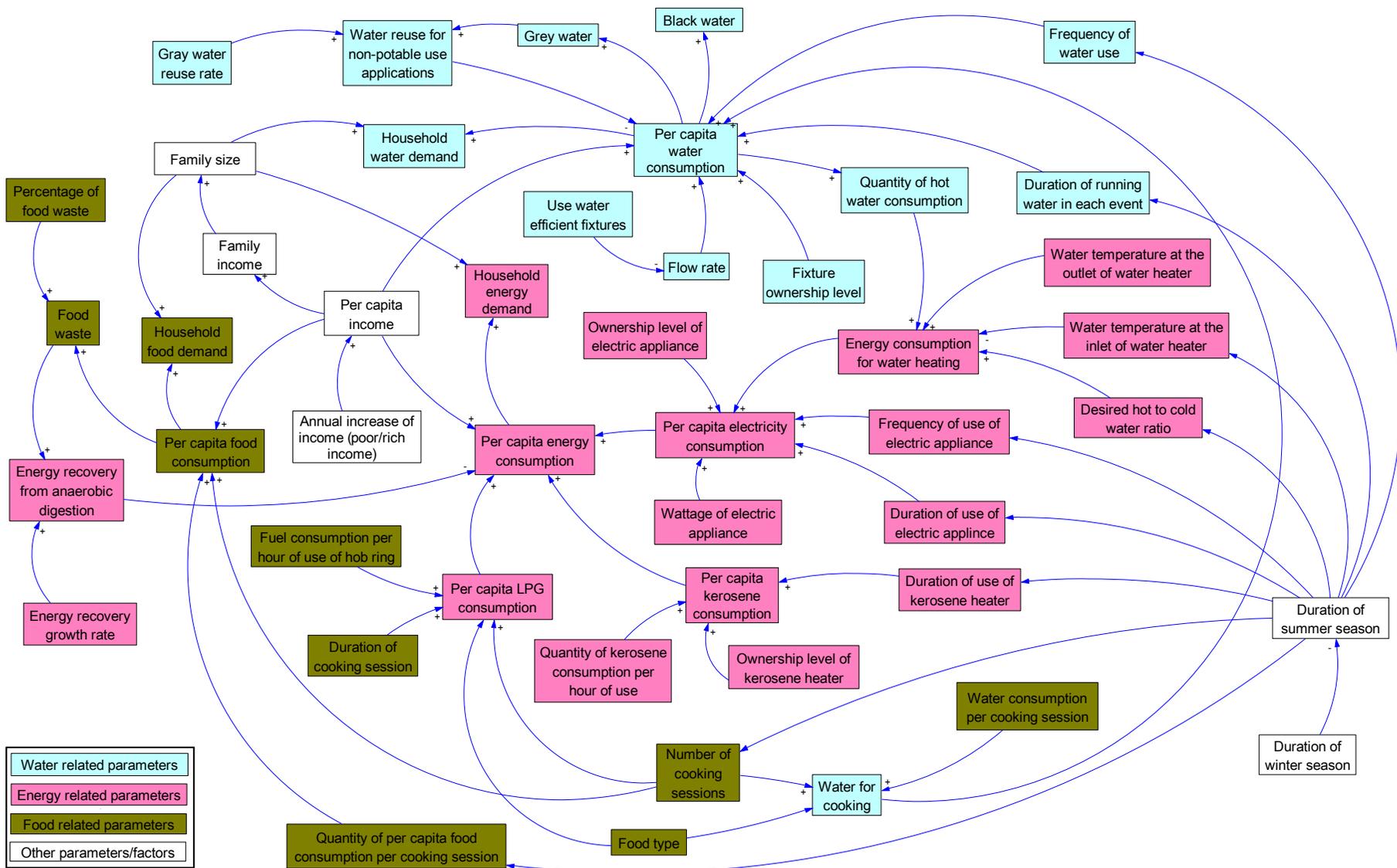
119 The model components have over 300 variables in total and a simplified version of
120 the model components is presented in Figure 1. The values of all input variables and
121 parameters into the model depend on the trend and pattern of water, energy and
122 food end-uses for the particular region. The detailed explanation of these variables

123 and the mathematical equations which describe the relationships between water,
 124 energy and food are explained in Sections 2.1 to 2.6.

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



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



152

153

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

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

161 **2.1 Modelling of household water consumption**

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

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

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

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

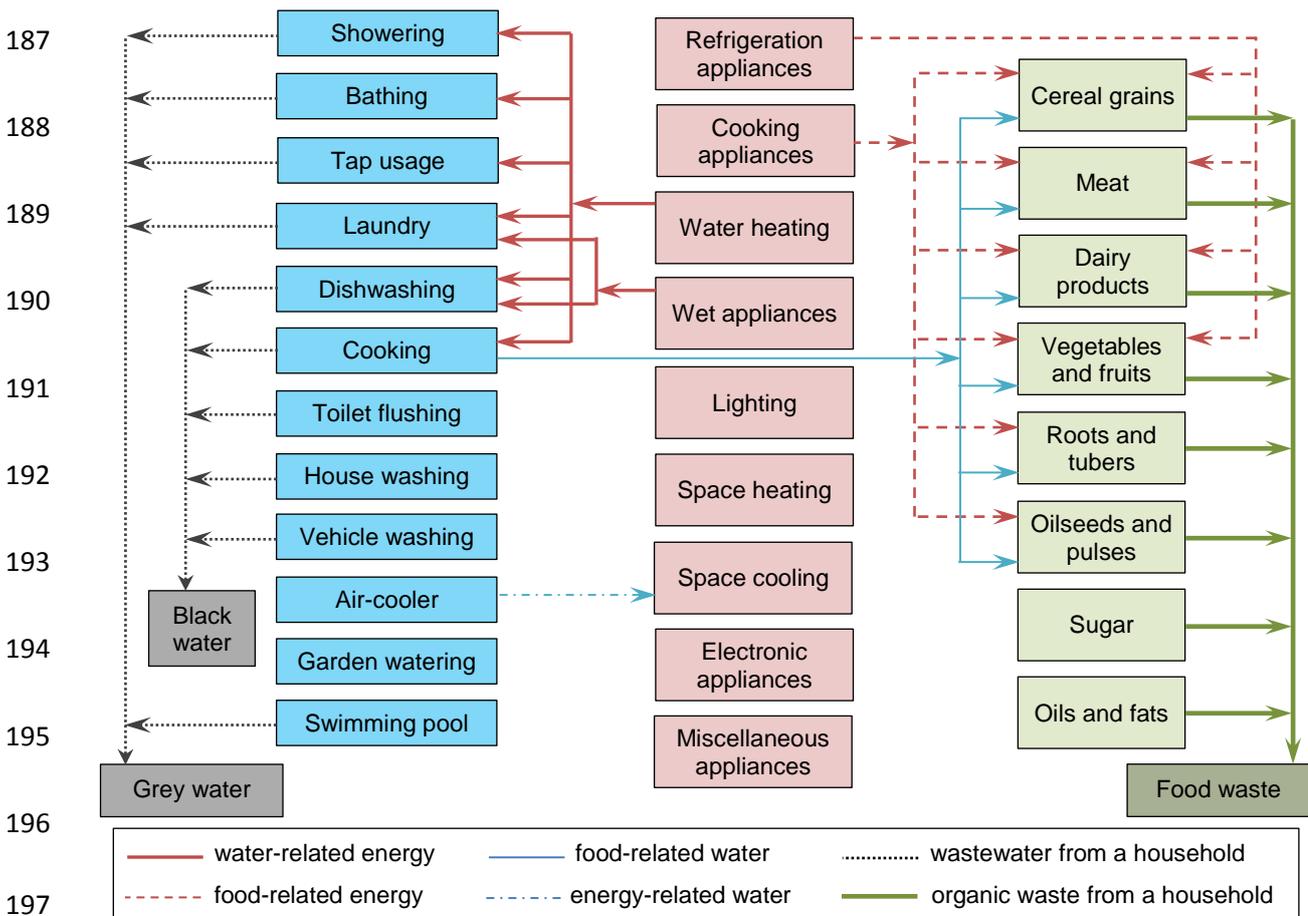
Ve_i = quantity of water consumption during each event of water end-use i (l/event).

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

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

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

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



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

200 **2.2 Modelling of household energy consumption**

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

208 **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

209 **2.2.1 Energy consumption for water heating**

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

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

219

220 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 ($1000 \text{ kg}/m^3$),

S = specific heat capacity of water = $4.186 \text{ kJ}/\text{kg } ^\circ\text{C}$,

T_{out} = water temperature at the heater outlet ($^\circ\text{C}$),

T_{in} = water temperature at the heater inlet ($^\circ\text{C}$), and

3600 = conversion factor (from kJ to kWh).

221 Swan (2010) assumed that the delivered water temperature, T_{out} , is $55 \text{ }^\circ\text{C}$ and T_{in} is
222 equal to the annual average soil temperature. In order to achieve the preferred tap
223 water temperature (40°C), it is assumed that 50% of the water used requires heating
224 (i.e., for bathing, showering, taps, dishwashing, laundry and cooking) (Kenway et al.,
225 2008; Fidar, 2010). For the case study in this paper, the same proportion has been
226 assumed for each indoor end-use requires heating to calculate the average per
227 capita hot water consumption. The average temperature of water supply (T_{in}) for the
228 case study is approximately $12 \text{ }^\circ\text{C}$ during the cold season (Duhok Directorate of
229 Seismology and Meteorology, 2015). The average water temperature at the outlet of
230 heater (T_{out}) is taken as 62°C , based on the survey findings. Using the quantity of per
231 capita hot water consumption and Equation 5, the per capita electricity consumption
232 for water heating can be calculated. The model is flexible to accommodate any hot to
233 cold water ratio (components no. 1 in Figure 1) considering various climatic
234 conditions in different regions of the world.

235 2.2.2 Energy consumption of electric appliances

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

243

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

244 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),

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

247 **2.2.3 Kerosene and LPG consumption**

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

$$E_s = N_s \times D_s \times Q_s \quad \text{Equation 7}$$

252 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).

253 **2.3 Modelling of household food consumption**

254 Household food consumption is disaggregated into several groups: cereal grains,
255 meat, dairy products, vegetables and fruits, roots and tubers, oilseeds and pulses,
256 oils and fats, and sugar. Each food group comprises various commodities as shown
257 in Table 2. The food commodities presented in this table are included in the WEF
258 model. The daily per capita consumption of each of these food commodities is
259 modelled as a function of the number of cooking sessions per day and the quantity of
260 food consumed per cooking session (components no. 3 in Figure 1) as shown in
261 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

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

263 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).

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

269 2.3.1 Water use for food preparation

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

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

275 where:

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

N_{c_i} = average number of cooking sessions of food commodity i per week (cs/w),
and

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

276 **2.3.2 Energy use for food preparation**

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

$$E_i = (N_{c_i}/7) \times (D_{c_i}/60) \times E_h \quad \text{Equation 10}$$

284 where:

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

D_{c_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).

285 **2.3.3 Food waste from household**

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

295 household income and seasonal variability. The values in Table 3 can be used in the
 296 developed model to quantify food waste in the regions of interest.

297 **Table 3 Percentage of waste from various types of food within the**
 298 **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

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

299 where:

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

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

300 **2.4 Impact of income on water, energy and food**

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

311 The households are divided into three income groups (i.e., low, medium and high)
 312 based on the classification of CSO and KRSO (2012) (Table 4). Based on this
 313 classification, the parameters relating to water, energy and food end-uses
 314 (components no. 1, 2 and 3 in Figure 1), which are presented in Section 2.1 to 2.3,
 315 are classified and defined in the model for each income group, individually. The

316 values assigned to these parameters are derived from the two surveys conducted as
 317 discussed in **Section 4.2**. The input parameter values to quantify water demand in
 318 the model can be found in Hussien et al. (2016). Consequently, the model estimates
 319 water, energy and food consumption for low, medium and high income households.

320 **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	$<1 \times 10^6$	$1 \times 10^6 - 2 \times 10^6$	$>2 \times 10^6$
Per capita	$<15 \times 10^4$	$15 \times 10^4 - 30 \times 10^4$	$>30 \times 10^4$

321 **2.5 Impact of seasonal variability on water, energy and food**

322 The household energy consumption varies seasonally due to changes in the energy
 323 requirements for space heating and cooling (Lam et al., 2008). Svehla (2011)
 324 showed a significant seasonal variation in refrigeration, cooking and the use of some
 325 other appliances. Most studies assumed that indoor water consumption, except for
 326 evaporative air-cooling, remains unchanged throughout the year (Rathnayaka et al.,
 327 2015). However, **in addition to garden watering, swimming pool and evaporative air-**
 328 **cooling, indoor water end-uses do vary seasonally**. An example is showering, which
 329 increases in summer (Rathnayaka et al., 2015).

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

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

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

337 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).

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

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

342 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).

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

354 2.6 Family size

355 The analysis of our conducted survey (Hussien et al., 2016) strongly suggests that
 356 Duhok family size is influenced by family income. Therefore, in the WEF model, the

357 impact of a family size (FS) is addressed as a function of increase/decrease in the
 358 family income (Equation 14).

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

359 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.

360 **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

361 **3 MODEL ASSUMPTIONS**

362 The key assumptions include:

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

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

383 **4 MODEL APPLICATION**

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

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

397 **4.1 Model input parameters**

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

406

Table 6 Summary of model input parameters

Input parameters	Key driver/end-use
Average family size of low, medium and high income households (FS_i)	Key drivers
Proportion of low, medium and high income households (P_i)	
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, toilet 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 (Na_i)	Kerosene heater, kerosene hob, gas heater, gas hob and gas oven
Duration of use of kerosene and gas use appliance (Ds_i) *	
Quantity of kerosene/gas consumption by the appliance (Qs_i)	
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 (Eh_i) *	
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 °C 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 1664.9×10^3 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

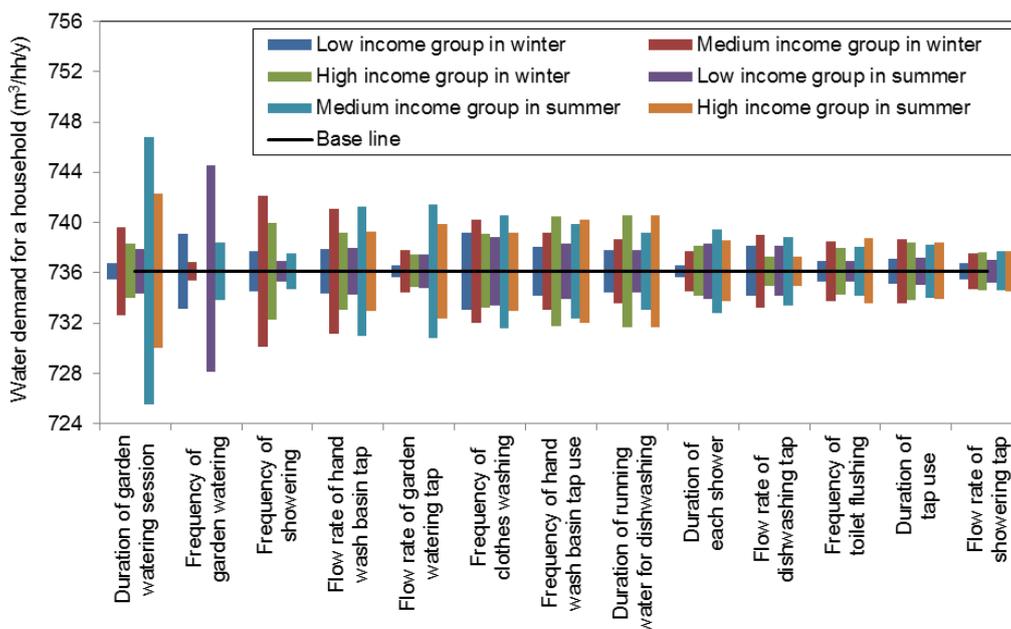
Using the case study of Duhok, the sensitivity of the WEF model estimations to the input parameters is analysed. The model validity is tested using uncertainty assessment analysis. Then the model results are compared with the historical data.

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

432 5.1 Model sensitivity

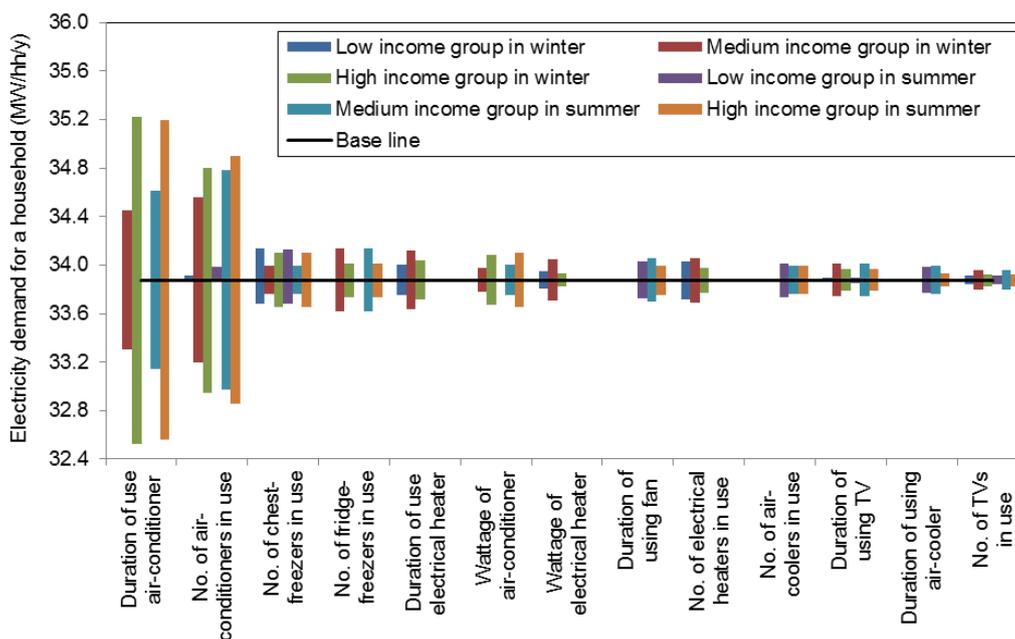
433 In order to calculate the sensitivity of the model output to the input parameters, **one-**
 434 **at-a-time analysis method has been used.** This method considers the range of
 435 variation in input parameters as its standard deviation below and above its average
 436 value (i.e., average \pm standard deviation) (Hamby, 1995). Then, the change in model
 437 output (water and energy demand) is quantified by using the upper and lower value
 438 of each input parameter individually, while holding all other input parameters at their
 439 base-case value (Cullen and Frey, 1999). **This method does not account for**
 440 **interactions between the input parameters (Frey and Patil, 2002; Saltelli and Annoni,**
 441 **2010), but provides a clear indication how a single parameter influences the overall**
 442 **outcome.**

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



448 **Figure 4 Sensitivity analysis of household water demand estimation to the**
 449 **input parameters**
 450

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



459 **Figure 5 Sensitivity analysis of household electricity demand estimation to the**
 460 **input parameters**
 461

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

465 5.2 Uncertainty analysis

466 The uncertainty of model output is analysed using the Monte Carlo technique. This
 467 technique has been used by Kenway et al. (2013) and Schaffner et al. (2009) to test
 468 the uncertainty of their models. For each input parameter into the WEF model,
 469 random values are selected from the distribution of possible values for input
 470 parameter under consideration. The random values of input parameters are used in
 471 the developed model and the expected value of the output is calculated to evaluate

472 the impact of multiple uncertain parameters. The process is repeated for a number of
 473 iterations. Then, the probability distribution of the calculated outputs is plotted as
 474 shown in Figure 6. The analysis shows that the uncertainty for water demand
 475 estimation is lower than that for energy. This is because the relative width (standard
 476 deviation/average (Schaffner et al., 2009)) of estimated demand for water (0.03) is
 477 less than that for electricity, kerosene and LPG (0.04, 0.04 and 0.05, respectively).
 478 The relative width of estimated demand for food types in Figure 6 is less than 0.04.

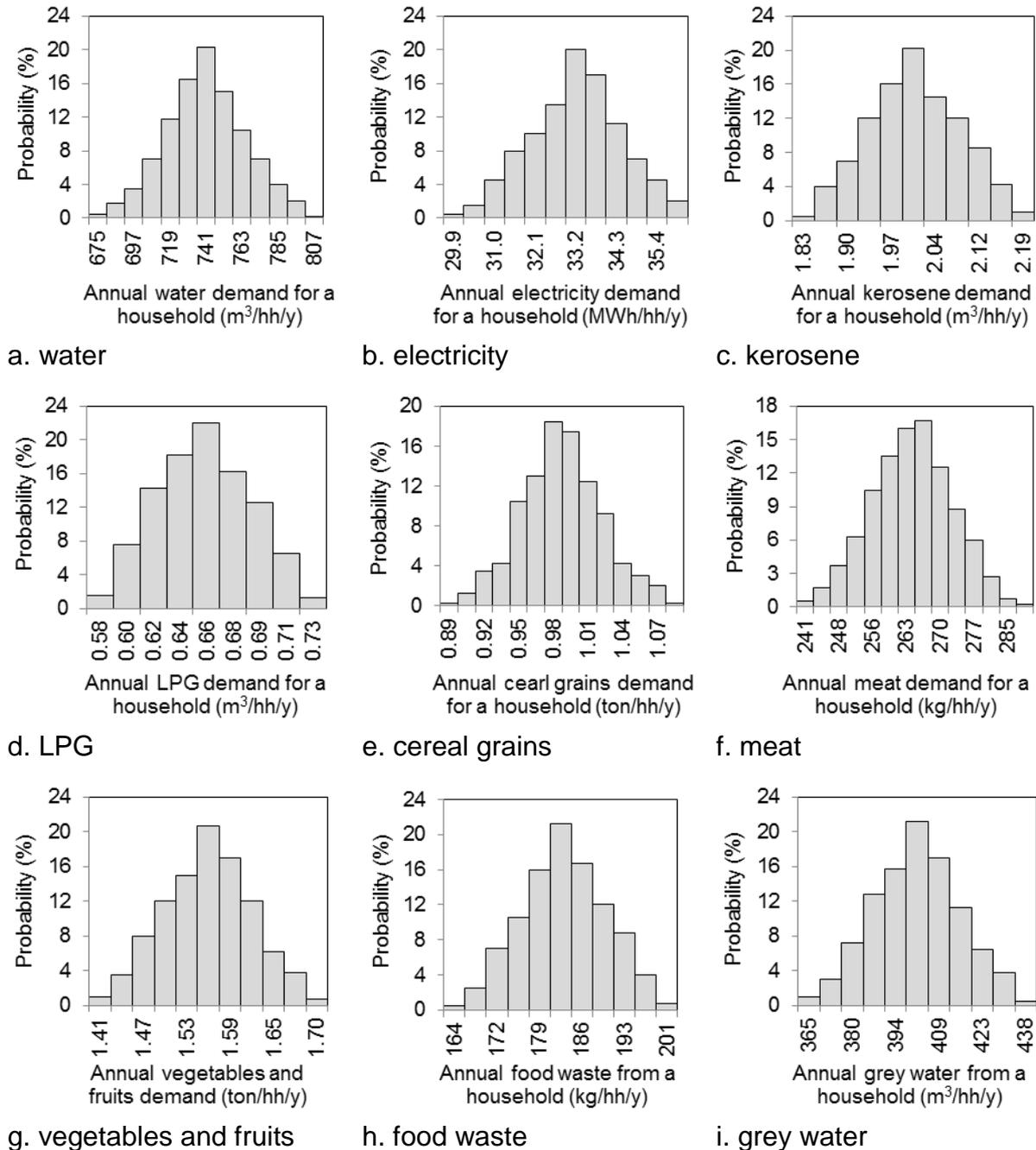


Figure 6 Probability distributions of Monte Carlo simulations

480 **5.3 Comparison of WEF model results with historical data**

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

493 **Table 8 comparison of model results with historical measured data at a**
 494 **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	
roots and tubers consumption	g/hh/d	933	529	COSIT et al. (2010)
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	
average family size	no.	7.04	6.7	CSO and KRSO (2012)

495

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

504 **5.4 Scenarios analysis**

505 The implications of Global Scenario Group¹ scenarios on water, energy and food
 506 demand are investigated in this paper. The scenarios are explained in Table 9.

507 **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.

508

¹ <http://gsg.org>

509 Numerous studies and assessments have relied on GSG scenarios, such as OECD
 510 (2001), WWV (2000) and UNEP (2002). According to GSG, water, energy and food
 511 consumption and poor/rich income ratio are assumed to vary from region to region.
 512 For the case study located in Iraq, values associated with the Middle East have been
 513 used as given in Table 10. The growth rates in this table reflect percentage change
 514 in consumption. The model initially used to calculate the base consumption, based
 515 on parameter values obtained from the survey. The consumption in each scenario is
 516 then calculated by the household WEF model using respective values for poor/rich
 517 income ratio in Table 10. The annual demand for water, energy and food has been
 518 simulated for 35 years ahead. The time horizon of 35 years is the most often
 519 considered timeline in scenarios (Hunt et al., 2012; Ercin and Hoekstra, 2014) and
 520 also recommended for socioeconomic planning (Simonovic and Fahmy, 1999).

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

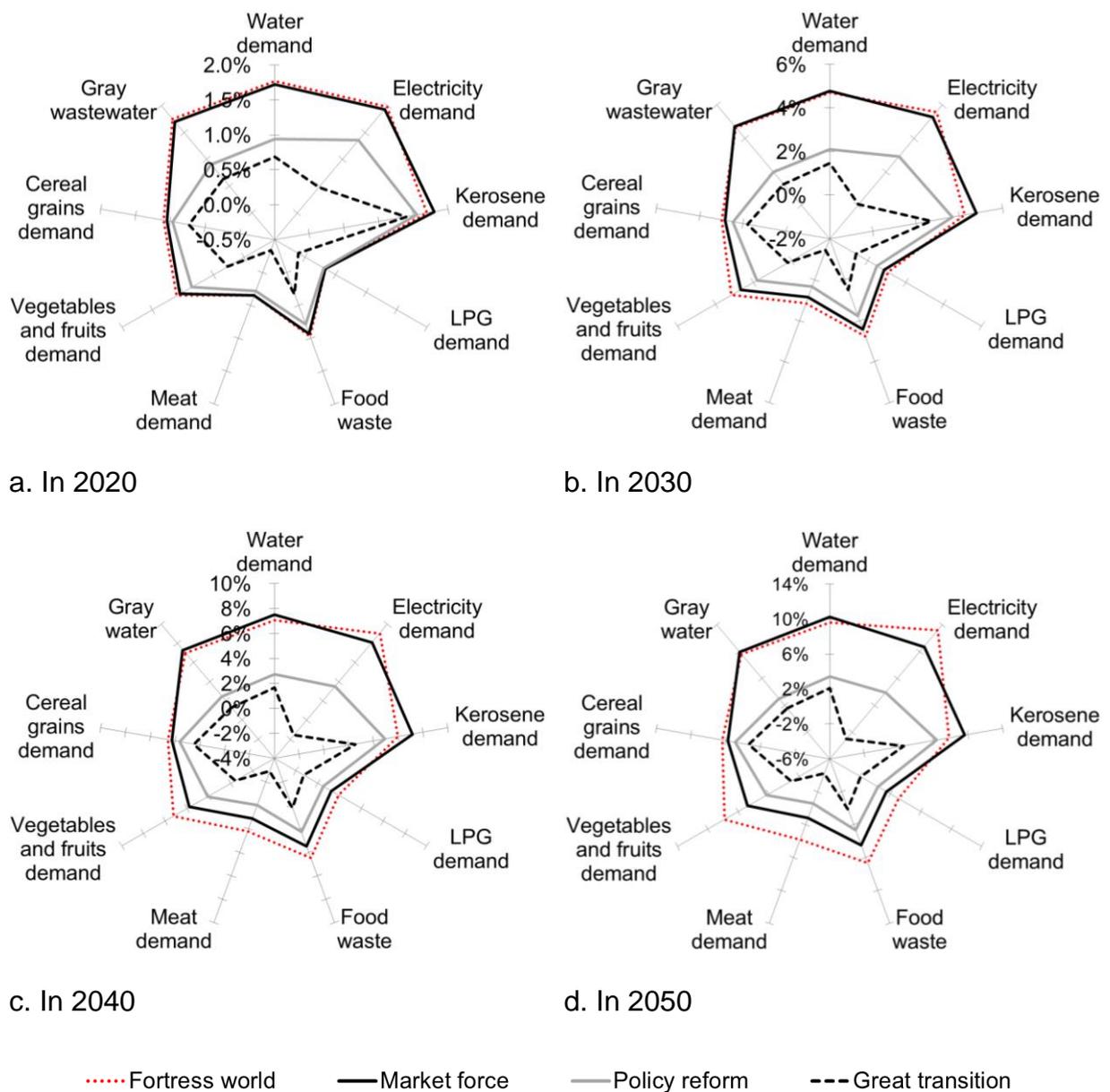
Indicators	Market force		Policy reform		Fortress world		Great transition	
	2005-2025	2025-2050	2005-2025	2025-2050	2005-2025	2025-2050	2005-2025	2025-2050
Poor/rich income ratio	0.03	0.03	0.2	0.15	-0.1	-0.3	0.6	0.5
Meat consumption	0.7	0.6	0.9	0.7	0.7	0.2	0.9	0.3
Crop consumption	2.1	1.4	2.0	1.2	2.2	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

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

529 The impact of GSG scenarios on the interactions between water, energy and food is
 530 also simulated as shown in Table 11. The results in this table show that the food-
 531 related energy in fortress world scenario is higher than the other scenarios. The
 532 water-related energy in market force scenario is slightly higher than that in the
 533 fortress world scenario. At a household level, the impacts of different scenarios are

534 marginal (Table 11). However, when extrapolated to a city level, noticeable
 535 differences and resources implication were observed.

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



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

543 **Table 11 The impact of GSG scenarios on the interactions between water,**
 544 **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

545 **6 CONCLUSION**

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

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

568 **Software, WEF model and data availability**

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

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

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

577 Software size: 27 MB

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

579 Name of the developed model: WEF model

580 WEF model developer and contact address: Wa'el A. Hussien, Fayyaz A. Memon
581 and Dragan A. Savic. University of Exeter, Exeter, Devon, UK. E-mail:

582 wahh201@exeter.ac.uk

583 WEF model data availability: provided as supplementary material

584 **Acknowledgment**

585 This work was financially supported by the Human Capacity Development Program
586 in Higher Education (HCED) in Kurdistan, Iraq. **We acknowledge** the support for this
587 work provided by Dr. Sarah Ward and Ziyad Ahmed.

588 **References**

589 Abdallah, A.M. and Rosenberg, D.E., 2012. Heterogeneous residential water and energy linkages and
590 implications for conservation and management. *Journal of Water Resources Planning and*
591 *Management*, 140(3), 288-297.

592 Aguilar, C., White, D.J., and Ryan, D.L., 2005. Domestic Water Heating and Water Heater Energy
593 Consumption in Canada.

594 **Anker-Nilssen, P., 2003. Household energy use and the environment - a conflicting issue. Applied**
595 **Energy, 76(1-3), pp.189-196.**

596 Arpke, A. and Hutzler, N., 2006. Domestic Water Use in the United States: A Life-Cycle Approach.
597 *Journal of Industrial Ecology*, 10(1-2), pp.169-184.

598 Aydinalp, M., Ugursal, V.I. and Fung, A.S., 2002. Modeling of the appliance, lighting, and space-
599 cooling energy consumptions in the residential sector using neural networks. *Applied Energy*,
600 71(2), pp.87-110.

601 Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A.,
602 Komorg, P., Tol, R.S.J., and Yumkella, K.K., 2011. Considering the energy, water and food
603 nexus: Towards an integrated modelling approach. *Energy Policy*, 39(12), pp.7896–7906.

604 Biggs, E.M., Bruce, E., Boruff, B., Duncan, J.M.A., Horsley, J., Pauli, N., McNeill, K., Neef, A., van
605 Ogtrop, F., Curnow, J., Haworth, B., Duce, S., and Imanari, Y., 2015. Sustainable development
606 and the water–energy–food nexus: A perspective on livelihoods. *Environmental Science and
607 Policy*, 54, pp.389–397.

608 Bonn Nexus Conference, 2011. *The Water Energy and Food Security Nexus – Solutions for the
609 Green Economy*. Germany.

610 Central Statistics Organisation (CSO), Kurdistan Regional Statistics Office (KRSO) and United
611 Nations Children’s Fund (UNICES), 2006. *Iraq Multiple Indicator Cluster Survey 2006, Volume 2:
612 Final Report*.

613 Central Organization for Statistics and Information Technology (COSIT), the Kurdistan Region
614 Statistics Office (KRSO) and the Nutrition Research Institute of the Ministry of Health (NRI),
615 2010. *Food deprivation in Iraq*.

616 Central Statistical Organisation (CSO) and Kurdistan Regional Statistics Office (KRSO), 2012. *Iraqi
617 household socio-economic survey report*.

618 Cheng, C.L., 2002. Study of the inter-relationship between water use and energy conservation for a
619 building. *Energy and Buildings*, 34(3), pp.261–266.

620 Cominola, A., Giuliani, M., Castelletti, A., Abdallah, A.M., and Rosenberg, D.E., 2016. Developing a
621 stochastic simulation model for the generation of residential water end-use demand time series.
622 In *Proceedings of the 8th International Congress on Environmental Modelling and Software
623 (iEMSs 2016)*, Toulouse, FR, 10-14 July 2016.

624 Cullen, A.C. and Frey, H.C., 1999. *Probabilistic Techniques in Exposure Assessment*. Plenum Press:
625 New York.

626 Daioglou, V., Van Ruijven, B.J. and Van Vuuren, D.P., 2012. Model projections for household energy
627 use in developing countries. *Energy*, 37(1), pp.601-615.

628 Demerchant, E.A., 1997. *User’s influence on energy consumption with cooking systems using
629 electricity*. PhD thesis. Virginia Polytechnic Institute and state University.

630 Djanibekov, U., Finger, R., Guta, D.D., Gaur, V., and Mirzabaev, A., 2016. A generic model for
631 analysing nexus issues of households’ bioenergy use.

632 Duhok Directorate of the Municipalities, 2014. [data collection].

633 Duhok Directorate of Seismology and Meteorology, 2015. [data collection].

634 Endo, A., Burnett, K., Orenco, P.M., Kumazawa, T., Wada, C.A., Ishii, A., Tsurita, I., and Taniguchi,
635 M., 2015. Methods of the Water-Energy-Food Nexus. *Water*, 7(10), pp.5806–5830.

636 Ercin, A.E. and Hoekstra, A.Y., 2014. Water footprint scenarios for 2050: A global
637 analysis. *Environment international*, 64, pp.71-82.

638 Fidar, A.M., 2010. *Environmental and economic implications of water efficiency measures in
639 buildings*. Ph.D. thesis, University of Exeter.

640 Flower, D.J.M., 2009. *An integrated approach to modelling urban water systems* (Doctoral
641 dissertation, Monash University. Faculty of Engineering. Department of Civil Engineering).

642 Food and Agriculture Organization (FAO), 2004. Human Energy Requirements: Report of a Joint
643 FAO/WHO/UNU Expert Consultation. FAO Food and Nutrition Technical Report Series No.1.
644 Rome: FAO.

645 Food and Agriculture Organization of the United Nations (FAO), 2011. Global food losses and food
646 waste-extent, causes and prevention. Rome, Italy.

647 Frey, H.C. and Patil, S.R., 2002. Identification and review of sensitivity analysis methods. *Risk*
648 *analysis*, 22(3), pp.553-578.

649 General Directorate of Duhok Electricity, 2014. [data collection].

650 Gettys, W., Keller, F. and Skov, M., 1989. Physics: Classical and Modern. McGraw-Hill Books
651 Company, 380.

652 Goldner, F.S., 1994. Energy Use and Domestic Hot Water Consumption. New York State Energy
653 Research and Development Authority, Report 94-19.

654 Grafton, R.Q., Ward, M.B., To, H. and Kompas, T., 2011. Determinants of residential water
655 consumption: Evidence and analysis from a 10-country household survey. *Water Resources*
656 *Research*, 47(8).

657 Hamby, D.M., 1995. A comparison of sensitivity analysis techniques. *Health Physics*. 68:195-204.

658 Hermann, S., Welsch, M., Segerstrom, R.E., Howells, M.I., Young, C., Alfstad, T., Rogner, H.H. and
659 Steduto, P., 2012, November. Climate, land, energy and water (CLEW) interlinkages in Burkina
660 Faso: An analysis of agricultural intensification and bioenergy production. In *Natural Resources*
661 *Forum* (Vol. 36, No. 4, pp. 245-262).

662 Hewitt, J.A. and Hanemann, W.M., 1995. A discrete/continuous choice approach to residential water
663 demand under block rate pricing. *Land Economics*, pp.173-192.

664 Hunt, D.V.L., Lombardi, D.R., Atkinson, S., Barber, A., Barnes, M., Boyko, C.T., Brown, J., Bryson, J.,
665 Butler, D., Caputo, S. and Caserio, M., 2012. Using Scenarios to Explore Urban UK Futures: A
666 Review of Futures Literature from 1997 to 2011. Working Document.

667 Hussien, W.A., Memon, F.A., Savic, D.A., 2016. Assessing and modelling the influence of household
668 characteristics on per capita water consumption. *Water Resources Management*. Accepted: 30
669 March 2016.

670 Iraqi Ministry of Electricity, 2010. [data collection]. (<http://www.moelc.gov.iq/upload/upfile/ar/charter>).

671 Isaacs, N., Camilleri, M. and Pollard, A., 2004. Household energy use in a temperate climate.
672 American Council for Energy Efficient Economy 2004 Summer Study on Energy Efficiency in
673 Buildings, California, 23-28.

674 Jacobs, H.E. and Haarhoff, J., 2004. Structure and data requirements of an end-use model for
675 residential water demand and return flow. *Water SA* 30(3), pp.293–304.

676 Kadian, R., Dahiya, R.P. and Garg, H.P., 2007. Energy-related emissions and mitigation opportunities
677 from the household sector in Delhi. *Energy Policy*, 35(12), pp.6195-6211.

678 Kemp-Benedict, E., Heaps, C., Raskin, P., 2002. Global scenario group futures. Technical notes
679 Stockholm, Stockholm Environment Institute, Global Scenario Group 464.

680 Kenway, S.J., Priestley, A., Cook, S., Seo, S., Inman, M., Gregory, A., and Hall, M., 2008. Energy use
681 in the provision and consumption of urban water in Australia and New Zealand.

682 Kenway, S.J., Scheidegger, R., Larsen, T.A. Lant, P., and Bader, H., 2013. Water-related energy in
683 households: A model designed to understand the current state and simulate possible measures.
684 Energy and Buildings, 58, pp.378–389.

685 Khan, S., Yufeng, L., and Ahmad, A., 2009. Analysing complex behaviour of hydrological systems
686 through a system dynamics approach. Environmental Modelling Software; 24:1363–72.

687 Kojiri, T., Hori, T., Nakatsuka, J., and Chong, T.S., 2008. World continental modelling for water
688 resources using system dynamics. Physics and Chemistry of the Earth; 33:304–11.

689 Kriström, B., 2008. Residential Energy Demand. OECD Journal: General Papers, 2008(2), pp.95–
690 115.

691 Kurdistan Ministry of Agriculture and Water Resources, 2014. [data collection].

692 Kurdistan Ministry of Natural Resources, 2014. [data collection].
693 (<http://www.zanagas.com/English/information/lpg-in-iraq/>)

694 Kurdistan Regional Statistics Office (KRSO), 2014. [data collection].

695 Lam, J.C., Tang, H.L. and Li, D.H.W., 2008. Seasonal variations in residential and commercial sector
696 electricity consumption in Hong Kong. Energy, 33(3), pp.513–523.

697 Loring, P.A., Gerlach, S.C., and Huntington, H.P., 2013. The new environmental security: Linking
698 food, water, and energy for integrative and diagnostic social-ecological research. 3(4), pp.55–61.

699 Mereu, S., Sušnik, J., Trabucco, A., Daccache, A., Vamvakeridou-Lyroudia, L., Renoldi, S., Viridis, A.,
700 Savić, D. and Assimacopoulos, D., 2016. Operational resilience of reservoirs to climate change,
701 agricultural demand, and tourism: A case study from Sardinia. Science of the Total
702 Environment, 543, pp.1028-1038.

703 Okutu, D.A.V.I.D., 2012. *Urban Household Characteristics and Implications for Food Utilization in*
704 *Accra* (Doctoral dissertation, University of Ghana).

705 Organisation of Economic Co-operation, Development (OECD), 2001. OECD environmental outlook
706 Paris: OECD.

707 Palmer, J., Terry, N. and Kane, T., 2013. *Further Analysis of the Household Electricity Survey-Early*
708 *Findings: Demand Side Management. Department of Energy and Climate Change (DECC):*
709 *London, UK.*

710 Qi, C., and Chang, N.B., 2011. System dynamics modelling for municipal water demand estimation in
711 an urban region under uncertain economic impacts. Journal of environmental management,
712 92(6), pp.1628–41.

713 Rathnayaka, K., Malano, H., Maheepala, S., George, B., Nawarathna, B., Arora, M., and Roberts, P.,
714 2015. Seasonal Demand Dynamics of Residential Water End-Uses. Water, 7(1), pp.202–216.

715 Ren, Z., Foliente, G., Chan, W., Chen, D., Ambrose, M., and Paevere, P., 2013. A model for
716 predicting household end-use energy consumption and greenhouse gas emissions in Australia.
717 International Journal of Sustainable Building Technology and Urban Development, 4(3), pp.210–
718 228.

719 Saltelli, A. and Annoni, P., 2010. How to avoid a perfunctory sensitivity analysis. *Environmental*
720 *Modelling & Software*, 25(12), pp.1508-1517.

721 Sarker, R.C. and Gato-Trinidad, S., 2015. Developing a demand model integrating end uses of water
722 (DMEUW): structure and process of integration. *Water Science and Technology*, 71(4), pp.529-
723 537.

724 Schaffner, M., Bader, H.P. and Scheidegger, R., 2009. Modeling the contribution of point sources and
725 non-point sources to Thachin River water pollution. *Science of the Total Environment*. 407:
726 4902–4915.

727 Simonovic, S., 2002. World water dynamics: global modelling of water resources. *Journal of*
728 *Environmental Management*; 66:249–67.

729 Simonovic, S.P. and Fahmy, H., 1999. A new modeling approach for water resources policy
730 analysis. *Water resources research*, 35(1), pp.295-304.

731 Singh, P., and Gundimeda, H., 2014. Life Cycle Energy Analysis (LCEA) of Cooking Fuel Sources
732 Used in India Households. *Energy and Environmental Engineering*, 2(1), pp.20–30.

733 Stave, K.A., 2003. A system dynamics model to facilitate public understanding of water management
734 options in Las Vegas, Nevada. *Journal of Environmental Management*, 67:303–13

735 Svehla, K.M., 2011. A Specification for Measuring Domestic Energy Demand Profiles. M.Sc. thesis in
736 renewable energy systems and the environment.

737 Swan, L.G., 2010. Residential sector energy and GHG emissions model for the assessment of new
738 technologies. Ph.D. thesis, Dalhousie University, Halifax, Nova Scotia.

739 Swan, L.G. and Ugursal, V.I., 2009. Modeling of end-use energy consumption in the residential
740 sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews*, 13(8),
741 pp.1819–1835.

742 United Nations Environment Programme (UNEP), 2002. Global environmental outlook 3. London:
743 Earthscan. Available online at: <http://www.unep.org/geo/geo3/>.

744 Vanclay, J.K., 2014. Unsuspected implications arising from assumptions in simulations: Insights from
745 recasting a forest growth model in system dynamics. *Forest Ecosystems*, 1(1), pp.1-10.

746 Wallgren, C., and Höjer, M., 2009. Eating energy—Identifying possibilities for reduced energy use in
747 the future food supply system. *Energy Policy*, 37(12), pp.5803–5813.

748 Wenhold, F.A.M., Faber, M., van Averbek, W., Oelofse, A., van Jaarsveld, P., van Rensburg, W.S.J.,
749 van Heerden, I., and Slabbert, R., 2007. Linking small holder agriculture and water to household
750 food security and nutrition. 33(3), pp.327–336.

751 Willis, R.M., Stewart, R.A., Giurco, D.P., Talebpour, M.R., and Mousavinejad, A., 2013. End use water
752 consumption in households: impact of socio-demographic factors and efficient devices. *Journal*
753 *of Cleaner Production*, 60, pp.107–115.

754 World Economic Forum, 2011. *Water Security: The Water–Food–Energy– Climate Nexus*. Island
755 Press, Washington.

756 World Water Vision Commission Report (WWV), 2000. *A water secure world: vision for water, life and*
757 *the environment* London: Earthscan.