Environmental Modelling & Software 93 (2017) 366–380

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Position Paper

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

ARTICLE INFO

Article history:
Received 18 September 2016
Received in revised form
23 March 2017
Accepted 28 March 2017
Available online 7 April 2017

Keywords:
End-use
Household scale
Income
Seasonal variability
System dynamics modelling
Water-energy-food nexus

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.

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 Nexus Conference, 2011; World Economic Forum, 2011).

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

* Corresponding author. Centre for Water Systems, College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, UK.
E-mail addresses: wahh201@exeter.ac.uk, wael@uod.ac (W.A. Hussien).

http://dx.doi.org/10.1016/j.envsoft.2017.03.034
1364-8152/

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

Fig. 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 (Fig. 1). Many aspects of water, energy and food are addressed in this model, such as the generated wastewater and food waste from a household (Fig. 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 Fig. 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 2.1–2.6.

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 Fig. 2.

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 (Sections 2.1–2.5).

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 Fig. 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 Fig. 3, using Equation (3) and Equation (4).