Science of the Total Environment 639 (2018) 485–496

Contents lists available at ScienceDirect

Science of the Total Environment

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

National water, food, and trade modeling framework: The case of Egypt

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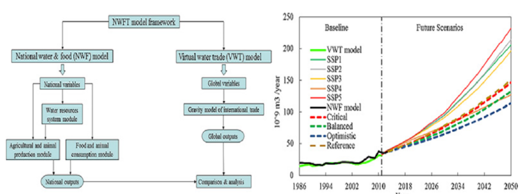
HIGHLIGHTS

- Virtual water trade should be considered when managing national water resources.
- Non-water based solutions can remediate water problems in water-scarce countries.
- Egypt's water and food gaps are projected to aggressively widen in the future.
- Both the global and national models projected similar patterns of Egypt's imports.
- NWFT modeling framework can be easily applied to any country in the world.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 13 March 2018
Received in revised form 15 May 2018
Accepted 15 May 2018
Available online 26 May 2018

Editor: D. Barcelo

Keywords:
Virtual water trade
Water footprint
Food consumption
Water resources system
Agricultural production
Future scenarios

ABSTRACT

This paper introduces a modeling framework for the analysis of real and virtual water flows at national scale. The framework has two components: (1) a national water model that simulates agricultural, industrial and municipal water uses, and available water and land resources; and (2) an international virtual water trade model that captures national virtual water exports and imports related to trade in crops and animal products. This National Water, Food & Trade (NWFT) modeling framework is applied to Egypt, a water-poor country and the world's largest importer of wheat. Egypt's food and water gaps and the country's food (virtual water) imports are estimated over a baseline period (1986–2013) and projected up to 2050 based on four scenarios. Egypt's food and water gaps are growing rapidly as a result of steep population growth and limited water resources. The NWFT modeling framework shows the nexus of the population dynamics, water uses for different sectors, and their compounding effects on Egypt's food gap and water self-sufficiency. The sensitivity analysis reveals that for solving Egypt's water and food problem non-water-based solutions like educational, health, and awareness programs aimed at lowering population growth will be an essential addition to the traditional water resources development solution. Both the national and the global models project similar trends of Egypt's food gap. The NWFT modeling framework can be easily adapted to other nations and regions.

1. Introduction

The natural hydrological cycle and the diversity of climatic regions in the world result in an uneven distribution, spatially and temporally, of

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https://doi.org/10.1016/j.scitotenv.2018.05.197

precipitation on land. Traditionally, societies relied on the engineering solution of constructing dams and creating artificial storage reservoirs to supply water-deficient regions with water at times of shortage. However, the engineering redistribution of water has a limited spatial impact when compared with the socioeconomic redistribution of water in its virtual form, which crosses national and continental boundaries. Water virtually embedded in products (Hoekstra et al., 2011) has its own human-induced cycle that can be seen as a socio-economic pendant to the natural hydrological cycle. People intervene on the hydrological cycle through water withdrawals from rivers, lakes and aquifers (i.e., blue water) and employing rainfall (i.e., green water) for agricultural production and other purposes. Through global trade networks (Dalin et al., 2012), virtual water flows along socioeconomic gradients, often from places of water surplus to places of shortage, sometimes reversely. Some countries even overexploit their water resources for economic gains through exports (Dalin et al., 2017). Globally, the large variability in water presence and the diversity of its use led to a global virtual water trade (VWT) network with bi-directional flows at every node – with each region being both a virtual water exporter and importer.

There is a significant body of literature on VWT (Allan, 2003; Hoekstra, 2013; Yang et al., 2006; Chapagain and Hoekstra, 2008; Hanasaki et al., 2010) and the development of VWT networks (Dalin et al., 2012; Suweis et al., 2011; Tamea et al., 2014). Most studies focused on the network structure and the variables controlling its behavior. For example, Dalin et al. (2012) found that the flows in the network can be reasonably explained with each nation's gross domestic product, mean annual rainfall, agricultural area, and population. Suweis et al. (2011) agreed with Dalin et al. (2012) regarding the importance of the gross domestic product and the annual rainfall. It was also concluded that the importing nations are expected to play an increasingly important role in the evolution of the future network dynamics. The increased connectivity of the global network highlights the risk of systemic disruptions and the resultant vulnerability of the global food supply, especially when exporting countries change to non-exporting at times of scarcity. Puma et al. (2015) suggested that this could happen in particular with regard to wheat and rice. The fact that over 80% of countries have low food self-sufficiency emphasizes the importance of investigating the VWT network and its future projections. The use of complex network theory (Barabási and Albert, 1999; Newman et al., 2006) to characterize the global VWT network has been the common approach used, along with probability distributions to describe the number and strength of trade links (Konar et al., 2011; Carr et al., 2012). While studying the VWT network, Konar et al. (2012) also distinguished the trade in blue and green water, and found that as countries attempt to increase their food export, they tend to utilize more blue water (irrigation). Tuninetti et al. (2015, 2017) noted that there is a significant spatio-temporal variability in the water footprint of major crops, which of course contributes to global water savings and losses as a result of VWT (Chapagain et al., 2006).

The gravity model of international trade, a multivariate regression approach to explain bilateral trade flows, is a common approach to explain the trade flows in a VWT network (Tamea et al., 2014). Acknowledging its potential contribution to understand the global redistribution of virtual water flows, hardly can this stand-alone global modeling approach in its current form attract potential users and policy makers at scales where decisions are typically made. In order to be beneficial, virtual water trade information needs to better align to the needs of (water) resource managers and policy makers at the national scale (El-Sadek, 2010; Wichelns, 2001), and VWT models need to be used in combination with water models typically applied at national level to inform water allocation decisions.

Numerous studies focused on VWT on the national scale. For example, Schyns and Hoekstra (2014) assessed the added value of including the analysis of VWT in a national water resources study for Morocco. Schyns et al. (2015) analyzed Jordan's water security in the light of its high domestic water scarcity and high reliance on virtual water imports. In a case study for Tunisia, Chouchane et al. (2018) analyzed VWT patterns in relation to environmental and socioeconomic factors. Mekonnen and Hoekstra (2014) assessed Kenya's water resources use and availability and how the country can mitigate its water scarcity by increasing imports of water-intensive products. Karandish and Hoekstra (2017) demonstrated the importance for national water policy formulation of considering both international and interregional VWT in a case study for Iran. Zhuo et al. (2016) developed water footprint and virtual water trade scenarios for China, considering five driving factors of change: climate, harvested crop area, technology, diet, and population. El-Gafy (2014) developed a model to estimate the water footprint of wheat produced in Egypt and crop-related VWT under different scenarios and found that water saving can be achieved as a result of VWT. Even though many studies on national VWT consider changes of water use and VWT over time, none of them combine the analysis of national water use dynamics and global trade dynamics, and this is achieved in this paper. Future scenarios of changing national VWT should be validated or put in the context of future global VWT scenarios.

Water resource management cannot be seen as something restricted to just one specific nation or river basin (Hoekstra, 2011). On the one hand, consumption of food and other products in a country usually translates to water demands elsewhere (related to imported products). On the other hand, water demand in a country that relates to producing export products, aggravates national water demand beyond what one would expect given the consumption pattern of the national population (Hoekstra and Chapagain, 2008). Thus, water resources management on national scale should consider water in its entirety, i.e. in real and virtual forms.

Water-poor countries are in pressing need to manage their water needs (real and virtual forms), which demands for an approach that goes beyond managing the nationally available water resources. The aim of this paper is to introduce a new modeling approach for the analysis and possible management of both real and virtual water at a national scale. This approach should have the ability to accommodate the notion that national water resources analysis is to be embedded in and put in the context of a global analysis of water resources availability. Therefore, it should be possible to assess the virtual water trade with the rest of the globe, and the projected changes in imports and exports under different national and global scenarios. We consider here the case of Egypt, a water-poor country, a major food importer (FAO, 2017a), and the world's largest wheat importer, to exemplify the development of a national water, food, and trade (NWFT) modeling framework. The framework includes a system dynamics model of national water-food supply and demand and a gravity model of international virtual water trade, running in parallel for analysis and comparison.

2. Virtual water trade modeling: challenges and possible solutions

Existing virtual water trade (VWT) models (e.g., Carr et al., 2013; Fracasso, 2014; Sartori and Schiavo, 2015) are mainly data driven, employing some logically governing variables (drivers) to characterize historical VWT. The VWT models capture the patterns of exports and imports. A conceptual concern regarding the models is that each virtual water flux between two nodes in the network (VWT from region *i* to region *j*) is typically estimated by two gravity models (Tamea et al., 2014): one demand-driven export model to estimate trade of country *i* to country *j*, and another supply-driven import model to estimate trade of country *j* from country *i*. Eventually, a single flux value can be estimated as the average of the two calculated values of the same flux (Tamea et al., 2014; Tuninetti et al., 2016). As a result of the approach, the models do not preserve the global food (or virtual water) balance; i.e. the sum of all regions' exports is not equal to the sum of all imports, although averaging the dual estimates improves the models' fit of the data.