Ecological Modelling 353 (2017) 150–157

Contents lists available at ScienceDirect

Ecological Modelling

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

Dynamic forecasting of agricultural water footprint based on Markov Chain-a case study of the Heihe River Basin

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ARTICLE INFO

Article history:
Received 30 March 2016
Received in revised form
12 September 2016
Accepted 4 November 2016
Available online 10 November 2016

Keywords:
Agricultural water footprint
Markov Chain
System dynamics model
Forecast

ABSTRACT

Water footprint forecasting is essential to measuring the embodied water resource consumption and achieving the sustainable water governance. Agricultural sector is conventionally a water intensive sector and accounts for large amount of water consumption in the river basins. In this paper, a system dynamics model is combined with Markov Chain, considering economic development, agriculture water consumption, population and agricultural ecosystem, to forecast the total agricultural water footprint (AWF) as well as its pressure on the freshwater ecosystem. Wheat, coin, potato, alfalfa, vegetables and flax are chosen as representative crops for AWF accounting in the integrated model. A case study of the Heihe River Basin in China during 2010–2030 shows that, the AWFs are 9.67×10^8 m^3, 1.02×10^9 m^3, 1.05×10^9 m^3 and 9.27×10^8 m^3 under Baseline Scenario, Moderate Risk Scenario, High Risk Scenario and Sustainable Scenario, respectively. It is concluded that the improvement on agricultural water efficiency may decrease the AWF, which can be achieved by agricultural water conservation, irrigation canal construction, maintenance funding and investments, agricultural planting adjustment, and virtual water strategies.

1. Introduction

Water footprint (WF) was initially developed by Hoekstra and Hung (2002) with an analogy to ecological footprint as the volume of water needed for the production of goods and services consumed by the inhabitants of the region, which may provide a feasible benchmark to measure both water consumption level and carrying capacity to reflect the anthropogenic impacts on water resources. There are two main branches of water footprint studies. One is based on the input-output table to convert monetary flow into the material and energy flows in a given economy and account for the embodied water resource utilization along the supply chain (Schendel et al., 2007; Zhao et al., 2009, 2010; Wang et al., 2009; Cazcarro et al., 2012; White et al., 2015). However, due to the data accessibility, it is a barrier to combine input-output analysis with water footprint analysis and achieve the integrated assessment in the last few years. Hence, using consumption data to capture the actual water utilization based on local water consumption census is more feasible for water footprint analysis (Pfister et al., 2009; Verma et al., 2009; Ridoutt and Pfister, 2010; Mekonnen and Hoekstra, 2011; Mao and Yang, 2012; Shao and Chen, 2013). Different tools such as STIRPAT model have been incorporated into the water footprint framework to provide explicit underlying information for agricultural water footprint (AWF) metrics (Pfister et al., 2011; Zhao et al., 2014; Dong et al., 2013). The modified AWF analysis based on thermodynamics also composed a twig of footprint studies (e.g., Rosa and Dietz, 2012; Shafiei and Salim, 2013).

So far, some researchers have investigated the water footprint based on local water census at river basin scale. Bodini and Bondavalli (2002) measured water exchanges between different sectors of activity within the municipal borders, and investigated the water flows by network analysis. Hoekstra and Hung (2002) calculated the virtual water content of livestock products for the given river basin and, which was subsequently elaborated by Chapagain and Hoekstra (2004). To explore the driving forces behind the changes of AWF at the river basin scale, Yang and Zehnder, (2007) used the structural decomposition analysis to explore the economic factors influencing water footprint over time. Based on input-output approach, Zhi et al. (2013) illustrated the socioeconomic factors affecting AWF fluctuations of the Haihe River Basin in North China. Particularly, Feng et al. (2016) proposed a hybrid model to explore the AWF of Zhangye city and its driving factors under the

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http://dx.doi.org/10.1016/j.ecolmodel.2016.11.002

rapid urbanization process in the Heihe River Basin. Although the water footprint accounting has been investigated extensively, the variation trends and major external forces of AWF, which can meet the basic requirement of river basin planning and systematic regulation, are still very few. To address this issue, dynamic prediction of the AWF in river basin have aroused increasing attentions, which is particularly significant for documenting the water consumption by human activities (Bian et al., 2014; Che and Han, 2014; An et al., 2016; Wu et al., 2016). Although scenario analysis, regression analysis and system dynamics model concerning multiple socioeconomic factors, such as economic growth, improvement on water consumption efficiency, have been conducted (Christensen et al., 2004; Chi and Chen, 2009; Hagemann et al., 2013; Wang et al., 2013; Hou and Tang, 2014), more efforts are still needed to explore the transforming mechanism and influencing factors of the AWF in river basin in the long run.

The Markov Chain is a useful tool to explore the system transforming from one state to another during a concerning period (Anderson and Goodman, 1957; Balzter, 2000). It has been proved as a feasible approach to describe the inner transitions among all footprint categories (i.e., cropland, pasture, forest, and water resource etc.), thus facilitating our cognition of why and how the AWF changes. The Markov Chain has been widely applied to predicting the dynamics of both natural and artificial systems, especially the water utilization and structure change in multi-levels (Liu et al., 2010; Lambooy, 2011; Jin et al., 2012; Ling et al., 2012; Pahl-Wostl et al., 2013; Hannouche et al., 2016). Being expressed with the virtual water consumption as well as six typical crops in the concerned river basin, AWF and its intrinsic transition can be quantified by the integration of Markov Chain.

In this context, we proposed a Markov Chain-based dynamic model to predict the trends of AWF and investigate the interactions among footprint categories. In the following, technical details including study site, Markov Chain and the dynamic model construction process are provided. In Section 3, scenario setting and outcome of the dynamic system model are presented. Finally, a range of conclusions are listed in Section 4.

2. Materials and methods

2.1. Study site

The Heihe River Basin is located at the Northwest China, which belongs to arid-semi arid region. The whole river basin is divided into three regions: the upper, middle and lower reaches (see Fig. 1). Each section of the river shows quite different characteristics in terms of topography, water resource availability, total amount of population and social economic structure. The agricultural cropping region is concentrated in the middle reach of Heihe River Basin, connecting to the mountainous and snow cover in the upper stream and desert area in the downstream, which has intensive social economic activities. Although the agricultural sector accounts for only 37.8% of the local GDP in the Heihe River Basin, the agricultural water consumption contributes 87.6% of the total water consumption, (Gansu Statistic Office, 2012).

2.2. Markov Chain

Follows are the assumptions conformed to the framework of Markov Chain. It is assumed that all the AWF categories can be transformed, e.g., due to the adjustment of agricultural water consumption policy, water consumed by vegetables can be transformed into further processed products. The transformation of total AWF can be considered as the pattern of the consumed and lifestyle, e.g., more consumption on coin, wheat, vegetable, fruit and other categories may be attributed to the variation of lifestyle. Meanwhile, time homogeneity is assumed to represent that water consumption pattern relies on the current condition and is independent of the preceded transformation events. Finally, the average transfer state of AWF is set as relatively constant along the concerned time series, which can be characterized as the transferring pattern of the total AWF.

Based on the mentioned assumptions, the transferring state of m order matrix is decided by the constitution of state set $\left\{A_1, A_2, \ldots . A_m\right\}$and transfer probability $t_{ij}\left\{i, j = 1, 2, \ldots, m\right\}$, which reflects the impact of various random factors on the whole. Therefore, each state of the system can be represented by random variables, corresponding to a specific probability termed as state probability.

Markov process state and the interrelationship can be realized by Markov Chain equation given as:

$$T_{t+1} = T_0[\boldsymbol{T}^{(1)}]^{t+1} \tag{1}$$

where, T_{t+1} represents the probability distribution at $t+1$ state, $T_0$is the unconditional probability distribution, $\boldsymbol{T}^{(1)}$ is the transfer probability matrix by one step, which can be further formulated as:

$$T^{(1)} = \begin{bmatrix} t^{11} & t^{12} & \cdots & t^{1m} \\ t^{21} & t^{22} & \cdots & t^{2m} \\ \vdots & \vdots & \vdots & \vdots \\ t^{1m} & t^{2m} & \cdots & t^{mm} \end{bmatrix} \tag{2}$$

where, $T^{ij}$is transfer probability and independent of initial states, which represents the probability of state t^n in the state of a_i transfer by one step to t^{n+1} moment of $a_j$state and expressed as:

$$t^{ij} = T(X_{n+1} = a_j | X_n = a_i),\ 0 \le t^{ij} \le 1, \sum_{j=1}^{n} t_{ij} = 1\ \ (i, j = 1, 2, \ldots.\text{m, n}).$$

The dynamic variation of AWF structure of the Heihe River Basin that induced by consumption structure is considered as discrete time Markov Chain. The transferring behavior of the consumption structure of wheat, coin, potato, alfalfa, vegetables and flax is analyzed to investigate the variation of main crop consumption structure of the Heihe River Basin, upon which the dynamic simulation of AWF can be conducted and its future variation can be forecasted.

The state transferring probability matrix can be formulated as:

$$T = [t_i(j)] \tag{3}$$

where, $t_i(j)$is the percentage of the i-th crop in the consumption of agricultural sectors,$i = 1, 2\ldots.6$represent wheat, coin, potato, alfalfa, vegetables and flax, respectively;$j$is the dynamic simulation and forecast years, $j = 0, 1, \ldots m, \ldots. n-1$; when $j = 0$,$p_i(0)$ represents consumption structure of the i-th crop in the baseline year of 1991.

Dynamic series of crop structure in the Heihe River Basin can be formulated by 18 steps transformation probability matrices (X_i and X_j) that represent the variation of the AWF structure during 1991–2011 as below:

The dynamic series of the AWF of the Heihe River Basin can be formulated as the probability transformation matrix $\boldsymbol{X_i}$ and $\boldsymbol{X_j}$, which may depict the variation of the AWF of the Heihe River Basin as:

$$X_i = \begin{bmatrix} p_1(0) & p_2(0) & p_3(0) & p_4(0) & p_5(0) & p_6(0) \\ p_1(1) & p_2(1) & p_3(1) & p_4(1) & p_5(1) & p_6(1) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ p_1(n-1) & p_2(n-1) & p_3(n-1) & p_4(n-1) & p_5(n-1) & p_6(n-1) \end{bmatrix} \tag{4}$$