Assessing impacts of water regulations on alleviating regional water stress with a system dynamics model

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ABSTRACT

Many areas around the world are faced with water scarcity and virtual water can provide ways to resolve the problem. This paper presents a comprehensive water system based on a system dynamics model to assess how water regulations from the viewpoint of virtual water affect the regional water stress index in the Haihe River Basin, China. The results show that green water absorption, blue water consumption, virtual water flow, and water use efficiency play important roles in the water resources system. Water stress can be relieved by improving the infiltration coefficient, irrigation efficiency, industrial water use efficiency, and virtual water import.

Key words | blue water, Haihe River Basin, system dynamics model, water regulation, water stress index

INTRODUCTION

The World Water Assessment Programme’s 2014 report indicates that one-third of the world’s population is faced with water scarcity (WWAP 2014). Many areas in China, especially western and northern China, are confronted with moderate to severe water shortages, which can impede regional development (Grace et al. 2016). It is predicted that in 2030, the total national water shortage will reach nearly 200 billion m³ around the world. Anticipated population, rapid urbanization, economic growth, as well as climate change, are expected to further stress water resources, which may prolong extreme droughts, aggravate climate anomalies, impact food security, and so on (Haines et al. 2006; Aizebeokhai 2011).

Before the concept of virtual water content was established, common management for alleviating water stress included: cross-region water diversion projects (e.g. the South-to-North Water Transfer Project in China), protection of natural springs and ponds, rainwater collection, and use of less water-intensive sanitation techniques (Ashton 2002); however, these strategies focused only on physical water. Allan (1993) proposed the virtual water concept to describe the total volume of water used for agricultural products. Since the introduction of virtual water, many scholars had quantified and analyzed its impacts on regional water resources systems (Dietzenbacher & Velázquez 2007; Zeitoun et al. 2010). There are also many studies that discuss the effects of various regulations on regional water resources’ systems (Meng et al. 2015; Julius et al. 2016). However, few studies explore how water regulations alleviate regional water stress from the viewpoint of virtual water with a system dynamics (SD) model. This paper presents an integrated SD simulation model in the form a decision-support system of water resources system for the Haihe River Basin (HRB) in China. The specific objectives of this study are: (1) to analyze the specific composition of regional water supply and demand; (2) to quantitatively determine
the key and controllable elements in regional water resources systems; and (3) to quantify changes in water stress caused by different regulations from the viewpoint of virtual water and provide plausible measures to relieve regional water stress.

DATA, METHODS AND MODEL DEVELOPMENT

PROCESS

Study area

HRB is located in northern China (Figure 1), and it has an area of \( \sim 318,200 \text{ km}^2 \) (111.95°E–119.84°E, 35.01°N–42.72°N). It supports more than 10% of the population with only 1.5% of the water resources of the country. This region is classified as an area of severe water shortage with water resource use per capita of 270 m³/year, which is equivalent to 14.29% of China’s average. Approximately 69% of cultivated land is under continuous wheat-maize farming and agriculture in the HRB depends heavily on irrigation (White et al. 2013).

Data

The meteorological data used to calculate agricultural virtual water were extracted from China’s meteorological data sharing service system (http://cdc.cma.gov.cn/home.do). Crop yield, industrial gross domestic product (GDP), population, input–output table and other economic data were acquired from the statistical yearbooks and regional Bureau of Statistics.

Methods

Blue water footprint (WF) and green water footprint

The green WF is defined as rainwater that is stored in the soil and evaporated or consumed during production, mainly during crop growth. The blue WF refers to surface and groundwater that are consumed or evaporated during irrigation and crop growth. The green and blue WFs of primary crops can be calculated according to the following equations proposed by Hockstra et al. (2011):

\[
WF_{\text{green}} = \frac{CWU_{\text{green}}}{Y} = 10 \times \frac{ET_{\text{green}}}{Y} \\
WF_{\text{blue}} = \frac{CWU_{\text{blue}}}{Y} = 10 \times \frac{ET_{\text{blue}}}{Y}
\]

where \(WF_{\text{green}}\) is a crop’s green WF (m³/t), \(WF_{\text{blue}}\) is the blue WF; \(CWU_{\text{green}}\) and \(CWU_{\text{blue}}\) are the green and blue water consumption (m³/ha); the number 10 is the conversion coefficient to convert water depth (mm) to water volume (m³/ha); \(Y\) is crop yield (t/ha); and \(ET_{\text{green}}\) and \(ET_{\text{blue}}\) are defined as the evaporative demand (mm/d) satisfied by green and blue water, respectively.

Method of calculating virtual water flow (VWF) among regions

Based on input–output tables, a direct consumption coefficient matrix \(A\) and direct water consumption coefficient are calculated as follows:

\[
A = \begin{bmatrix} a_{ij} \end{bmatrix}, \quad a = \frac{x_{ij}}{x_j} \\
K_j = \frac{w_j}{x_j}
\]

where \(a_{ij}\) is the direct input from sector \(i\) needed to increase per monetary unit output in sector \(j\); \(x_{ij}\) is the investment in sector \(i\) during production of department \(j\); \(x_j\) is the total output of department \(j\); \(K_j\) is the direct water consumption coefficient; and \(w_j\) is the water consumption of sector \(j\).

The total water consumption coefficient is then calculated as:

\[
Q = K[I - A]^{-1} = [q_{ij}]
\]

where \(q_{ij}\) is the gross water input from sector \(i\) necessary per monetary unit of final demand in sector \(j\), and \(I\) is the identity matrix.

The net import of virtual water in a region is:

\[
W_{\text{net}} = QM - QE
\]
Figure 1 | Haihe River Basin in China.
where $W_{net}$ is the net virtual water import; $E$ and $M$ are output and input values in the column vectors of the input-output table.

**Water stress index (WSI)**

In this paper WSI refers to blue water stress and is calculated as follows:

$$WSI = \frac{(WA + WT)}{(WS + WE_{blue})}$$

where $WA$ is agricultural irrigation water demand; $WT$ is the total of industrial, domestic, and ecological water demand; $WE_{blue}$ is blue water imported from outside regions through virtual water trade; and $WS$ is the freshwater available in the region.

Blue water stress can be classified into four levels according to water scarcity: low water scarcity ($WSI < 1$), moderate water scarcity ($WSI = 1–1.5$), significant water scarcity ($WSI = 1.5–2$), and severe water scarcity ($WSI > 2$) (Hoekstra et al. 2012).

**SD model development**

The SD model in HRB includes six subsystems and the study period is 2000–2015.

**Agricultural irrigation water demand subsystem**

Agricultural water use amounts to about 70% of total regional water consumption. Cultivated crops include winter wheat, summer maize, rice, soybean, oil crops, cotton, vegetables, potato, watermelon, muskmelon, tobacco, and so on. From 1991 to 2015, the average annual WF of crops was 49.54 billion m$^3$, of which 25.58 billion m$^3$ are blue water. The virtual water of winter wheat, summer maize, rice, oil crops, cotton, and vegetables accounts for more than 90% of the regional agricultural virtual water. Therefore, the agricultural water requirements of these six crops can be substituted for the regional total agricultural water demand. During agricultural irrigation, the ratio of water absorbed by crops to the total volume of irrigation water is irrigation efficiency, and the ratio of blue water requirements to irrigation efficiency is the theoretical irrigation water demand. If the volume of green water increases, the blue water demand will decrease. Thus, the infiltration coefficient of precipitation during crop growth also plays important role in regional water resources systems.

**Industrial water demand subsystem**

In HRB, industrial virtual water consumption is 1.1–1.4 times larger than that of physical water during the period 1990–2015. This paper generalizes industrial virtual water consumption 1.2 times that of physical water. From 2001 to 2015, the physical water consumption of the industry decreased from 6.58 to 4.93 billion m$^3$ and the average industrial water consumption of per 10,000 yuan decreased from 90 to 7.25 m$^3$. Industrial water demand is intrinsically related to total industrial output and water consumption per unit of industrial output value.

**Household water demand subsystem**

Household water demand includes domestic water for rural residents and urban residents. During 2001–2015, household water consumption of rural residents and urban residents were 73 and 160 L per capita per day, respectively. Household water demand is related to both water consumption per capita and total population.

**Ecological water demand subsystem**

Ecological water demand mainly includes water consumption of green space. The calculation method is just the same as that of agricultural water demand.

**Blue water import subsystem**

The input–output analysis shows that in 2012 the net import virtual water in HRB was 5.32 billion m$^3$, of which agricultural virtual water accounted for ~72% and industrial virtual water accounted for ~29%. For the SD model in this paper, water scarcity indicates a shortage of physical water, and the volume of net imported virtual water should be transferred into blue water. For agricultural products in this region, blue water accounts for 60% of the
virtual water content; for industrial products, blue water is almost 83.3% of the virtual water content.

**Water supply sub model subsystem**

Water supply in HRB consists of surface water, groundwater and waste water after treatment, and desalinated seawater. Of these, surface water and groundwater are the main components. In 2015, groundwater, surface water and other water resources were 56.5%, 38.3% and 5.2% of the total water supply, respectively.

**RESULTS AND DISCUSSION**

**Model simulation**

**Stock-flow figure**

Figure 2 diagrams the basic dependencies of the variables in a water resources system based on the relationships among the variables. Nine level variables are designed which are maize yield, wheat yield, rice yield, cotton yield, vegetables yield, oil crops yield, gross industrial output value, green land area and total population, respectively. The SD model also takes into account nine constant variables, 25 auxiliary variables and 42 rate variables.

**Main equations**

The SD model for HRB is comprised of 43 equations (nine state equations, nine rate equations, and 25 auxiliary equations), as well as a number of table functions and constants by the variables listed in stock-flow figure parts (the equations are given in the appendix).

**Model test and sensitivity analysis**

The software program Vensim PLE6.3E is used to formulate and simulate the water resources system in HRB. Mean absolute percent error (MAPE) is a measure of prediction accuracy of a simulation method and usually expressed as

![Figure 2](http://iwaponline.com/ws/article-pdf/19/2/635/663781/ws019020635.pdf)
a percentage. It is calculated as follows:

\[ \text{MAPE} = \frac{1}{n} \sum \left| \frac{\text{real value} - \text{simulated value}}{\text{real value}} \right| \times 100 \]  

(6)

where \( n \) is the number of years involved in the calculation.

In this paper, real data in 2005, 2010, and 2015 are compared with the simulation data in the same period to test the predictive accuracy and stability of the SD model. The results are shown in Table 1.

Test results show that the MAPE for all variables is below 10%. Excluding household water consumption in 2005 and 2010, MAPE of all variables was less than 5%. The result of error analysis for the SD model indicates high model confidence.

To further establish model results confidence, sensitivity analysis was done to evaluate how model behavior is affected by uncertain variables change. For the sensitivity analysis, nine variables (Table 2, first column) were selected to be increased by 10% of their nominal values. During the analysis, only the values of selected parameters were offset and all other parameters were unchanged. Table 2 shows the results of a sensitivity analysis of population, industry GDP, WSI, industry WF, domestic WF, and irrigation water demand for the year 2015. The results indicate that population and domestic WF has low sensitivity to all statistical parameters (lower than 1%). Wheat yield, maize yield, infiltration coefficient, irrigation efficiency, water consumption of unit industrial output value and virtual water import have the most influence on industry GDP, WSI, industry WF and irrational water demand. Among the sensitive parameters to WSI, population cannot be controlled in a short time; wheat and maize yield should not reduce in China, so four variables are key control parameters in the SD model: infiltration coefficient, irrigation efficiency, water consumption of industrial unit output value and virtual water import.

Model simulation results

This paper calculates yearly WSI by using data from the statistical yearbook in an SD model. Water demand parameters included crop yield, yield variation rate, gross industrial output, industrial growth rate, and population. Values of infiltration coefficient, irrigation efficiency, water consumption of rural residents, urban residents, and the blue water proportion of imported agricultural virtual water were 0.7, 0.5, 75 (L/c/d), 160 (L/c/d), and 0.6, respectively. The WSI during 2000–2015 was between 1.74 and 2.14, indicating that HRB is experiencing significant and severe scarcity of water resources.

Infiltration coefficient

To mitigate water scarcity, use of precipitation during crop growth should be maximized. The current infiltration coefficient for agriculture is \(~0.7\), indicating that 70% of precipitation is converted into green water (effective precipitation). If the infiltration coefficient is increased to 0.77 with all other parameters unchanged, the simulated WSI is between 1.47 and 2.0. Thus, a 10% increase in infiltration coefficient can reduce WSI by \(~6.23–15.7\%\).

Irrigation efficiency

Data show that irrigation water in HRB is almost equal to the blue water demand; that is, if there is no loss in irrigation water, the crop water demand can be satisfied by irrigation.

| Test parameters | Real values | Simulated values | MAPE (%) |
|-----------------|-------------|-----------------|----------|
| Gross industrial output (10¹⁰ Yuan) | 190.07 | 463.78 | 796.68 | 181.56 | 458.92 | 783.7 | 4.48 | 1.05 | 1.63 |
| Household water consumption (10⁸ m³) | 55.53 | 59.0 | 66.78 | 58.76 | 62.46 | 66.69 | 5.82 | 5.86 | 0.13 |
| Winter wheat yield (10⁴ ton) | 2,524.15 | 2,980.01 | 3,201.5 | 2,435.08 | 2,939.23 | 3,220.91 | 3.53 | 1.37 | 0.61 |
| Summer maize yield (10⁴ ton) | 2,997.93 | 3,940.19 | 4,203.5 | 2,885.97 | 3,801.59 | 4,039.78 | 4.48 | 1.05 | 1.63 |
However, irrigation efficiency is 0.5 in HRB; meaning that crops absorb only 50% of irrigation water, and the remaining is lost as runoff. Improvement in irrigation efficiency can reduce the irrigation water demand. An increase in irrigation efficiency from 0.5 to 0.55 decreases WSI from 1.74–2.14 to 1.57–1.98.

**Water consumption of industrial unit output value**

Parameters of the industrial water demand sub-model include industrial output value, industrial output growth speed, and industrial *unit* output value. At present, industrial economic growth in HRB is improving, so water scarcity can be relieved by decreasing water consumption of *unit* industrial output value. A 10% reduction in this variable results in WSI of 1.74–2.13.

**Virtual water import**

Virtual water trade can alleviate water scarcity. If HRB can import more products rich in virtual water, that is, if imported water increases by 10%, WSI can be reduced to 1.52–2.13.

**Comprehensive regulations**

The WSI will be decreased if the four regulations described above are implemented individually, thereby alleviating water scarcity. If the four measures are implemented simultaneously, WSI can be lowered to 1.27–1.82, which reflects a moderate to significant water scarcity status.

**Policy implications**

This paper describes the development of an SD model to explore the characteristics of water resources in HRB. Controllable variables such as infiltration coefficient, irrigation efficiency, water consumption per unit industrial output value, and virtual water import were identified as key parameters. Without any regulations, water resources for HRB reflected significant or severe water scarcity during 2000–2015. The impact of comprehensive regulations can convert the water resources status to moderate or significant scarcity. Infiltration coefficient and irrigation efficiency are the most important variables for HRB's water resources system, and a 10% increase in both will reduce WSI by 6.3–15.7%. Improving the efficiency of green water use and blue water use can mitigate water scarcity.

Increasing the precipitation infiltration coefficient can help relieve water scarcity. Methods for improving the infiltration coefficient are described as follows. First, plastic film mulching is a common and effective practice that has been adopted worldwide for many years, especially in arid and semi-arid areas (Sharma et al. 2011). It can reduce soil evaporation and water consumption, change precipitation infiltration patterns, and increase rainfall runoff (Rice et al. 2007). The air permeability of the plastic film can hinder the evaporation of soil moisture to the outside.

### Table 2 | Results of sensitivity analysis (%)

| Parameters | Population | Industry GDP | WSI | Industry WF | Domestic WF | Irrigation water demand |
|------------|------------|--------------|-----|-------------|-------------|--------------------------|
| Population | 0.39       | 2.58         | 2.1 | 2.99        | 0.19        | 0.27                     |
| Wheat yield| 0          | 4.9          | 1.98| 3.67        | 0           | 3.91                     |
| Maize yield| 0          | 3.97         | 2.67| 4.01        | 0           | 4.82                     |
| Infiltration coefficient | 0 | 0.86 | -2.79 | 3.28 | 0 | -8.54 |
| Irrigation efficiency | 0 | 0.01 | -5.01 | 0.9 | 0 | -7.91 |
| Industrial output | 0 | 5.43 | 1.85 | 3.42 | 0 | 1.28 |
| Water consumption of industrial unit output value | 0 | 2.31 | -2.3 | 5.97 | 0 | -1.92 |
| Greenland area | 0 | 0.29 | 0.39 | 0.36 | 0.01 | 0.17 |
| Virtual water import | 0 | 0.75 | 0.8 | 0.71 | 0 | 2.23 |

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world, force water to move laterally which can slow down soil water loss speed and reduce total water drops loss. At the same time, the high temperature in the film and the airtight and watertight characteristics of the plastic film make the deep water in the soil accumulate under the film which make soil moisture rise to the plough layer.

Second, many experiments have indicated that straw mulching can improve water intake and storage and increase precipitation infiltration capacity (Mulumba & Lal 2008; Prosdocimi et al. 2016). For example, using winter wheat straw to cover summer maize enhances soil hydraulic properties, accelerates the infiltration rate of water, and increases moisture storage in deep soil. As a result, the water-holding capacity is improved, which can provide essential water for crop growth and reduce the blue water demand.

Improving irrigation efficiency requires reduction of water loss from irrigation canal systems during transportation of water to fields. Increasing water use efficiency in the field can be accomplished by improving engineering methods to prevent channel leakage; using low-pressure pipelines instead of ground conveying channels; employing advanced channel distribution software to realize the optimal allocation of irrigation water; and using water-saving technology such as drip irrigation, sprinkler irrigation, and film mulching irrigation. Second, to improve water use efficiency, reasonable irrigation regulations should be established, and irrigation time and quota should be determined according to the critical period of crop water requirement. Third, crop structure should be adjusted and arranged rationally according to the rainy season and the water requirement of crops so as to make full use of precipitation and cut down.

CONCLUSIONS

In this paper, the impact of various regulations from the viewpoint of virtual water on regional water stress is simulated by applying an SD model to HRB, China. Analyses documented that this region is experiencing significant scarcity of water resources under current development. Sensitivity analysis indicated that elements such as infiltration coefficient, irrigation efficiency, water consumption of industrial unit output value and virtual water import play important roles in the regional water resources system. Among the regulations, improving infiltration coefficient has the most positive impact on alleviating water stress.

In general, this model shows the important role of regulations in view of virtual water in a regional water resources system and the thought can provide a way to mitigate water stress for other water scarcity areas. However, it should be noted first that only the main elements of the water resources system are comprised in the modeling process and factors such as grey water, water quality, groundwater change and market-related factors are missed owing to data availability. Second, the factors in the model are generalized and it cannot completely reflect the complex water resources system. In the future, an SD model can be incorporated with a grey model and genetic algorithm to improve its utility.

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