Water footprint of Xiamen city from production and consumption perspectives (2001–2012)
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ABSTRACT
Providing a comprehensive insight, water footprint (WF) is widely used to analyze and address water-use issues. In this study, a hybrid of bottom-up and top-down methods is applied to calculate, from production and consumption perspectives, the WF for Xiamen city from 2001 to 2012. Results show that the average production WF of Xiamen was 881.75 Mm³/year and remained relatively stable during the study period, while the consumption WF of Xiamen increased from 979.56 Mm³/year to 1,664.97 Mm³/year over the study period. Xiamen thus became a net importer of virtual water since 2001. Livestock was the largest contributor to the total WF from both production and consumption perspectives; it was followed by crops, industry, household use, and commerce. The efficiency of the production WF has increased in Xiamen, and its per capita consumption WF was relatively low. The city faces continuing growth in its consumption WF, so more attention should be paid to improving local irrigation, reducing food waste, and importing water-intensive agricultural products.

Key words | consumption, production, urban, water footprint

INTRODUCTION
Fresh water is a scarce resource globally, especially in growing urban areas because of their high consumption demand, vigorous economic development, and population expansion (Liu & Yang 2012). China faces a severe water scarcity problem, as its per capita water resources are a quarter of the world’s average and two-thirds of its 669 cities have water shortages (Liu & Yang 2012). China is also experiencing an historically rapid urbanization process (Wang et al. 2015). Obtaining a comprehensive understanding of the water challenge faced by Chinese cities is therefore important.

Water footprint (WF) represents an opportunity for better water management and use; it measures the volume of water needed to produce the goods and services consumed by an individual person, business, region, or country (Hoekstra et al. 2012). The concept of WF was developed from virtual water (VW), which is defined as actual water used in the production of a commodity or service (Velázquez et al. 2010; Hoekstra et al. 2012). WF is usually used to address the total water consumption of a producer or a consumer, while VW is frequently used when talking about a product or service; VW is also widely used in the context of international or interregional trade. The WF of different areas can be linked by virtual water trade or flow. In addition, WF can be categorized into blue, green, and grey WFs (Chenoweth et al. 2015). The blue WF refers to surface and groundwater consumed during production, which is equal to direct water use in industries and households minus return flows. The green WF is defined as the use of soil moisture, also known as effective or productive precipitation. The grey WF is the volume of water used to assimilate the load of pollutants so that acceptable water quality standards are met. There have been many studies on product (Chapagain & Hoekstra 2005; Gerbens-Leenes et al. 2015), regional, national, and global WFs (Zang et al. 2012; Ercin et al. 2013; Ercin & Hoekstra 2014). The method presented
by Hoekstra is developed into the Water Footprint Assessment (WFA) approach (Hoekstra et al. 2012). Besides, another similar approach, namely ISO 14046, was also developed by the Life Cycle Assessment (LCA) community to address environmental impacts (Boulay et al. 2013; Kounina et al. 2013). Rather than LCA, the WFA approach was more widely used in studying water-related hot-spots and was found useful for guiding actions for improving water efficiency and management (Jefferies et al. 2012; Manzardo et al. 2016).

For a certain geographic area, the production water footprint (WFprod) is defined as the sum of direct and indirect water use in local production processes, while the consumption water footprint (WFcons) is the water resources used to meet the consumption of the goods and services in a given area (Ercin et al. 2013). WFcons and WFprod can reach a balance with net imported virtual water (VWni). The WF of a certain area can be calculated by two methods within the WFA method, top-down and bottom-up (Hoekstra et al. 2012). The bottom-up method is the adding up of the direct and indirect water use of the goods and services consumed or produced in a region. In the top-down method, WFcons is equal to WFprod plus imported virtual water minus exported virtual water. Compared to the top-down method, the bottom-up method is applied more widely because of better availability of data (Hoekstra et al. 2012). In addition, an input–output method has recently been widely used to analyze the water interconnections and interdependencies of economic units (Wang et al. 2013).

Xiamen city has been facing severe water shortages. Its per capita water resource is only 333.90 m³, which represents only about one-third of the international minimum standard (1,000 m³ per capita) (UNESCO 2016). To address the water problem, one must understand the structure and efficiency of water use and the interdependency of water use among cities. The concept of WF from production and consumption perspectives, using a hybrid bottom-up/top-down method, was therefore applied to analyze Xiamen’s water resource needs from 2001 to 2012. This paper is organized as follows: (1) information concerning the study area and an introduction to research scope, methodology, and data, (2) analysis of the WFs and virtual water trade, and (3) conclusion.

MATERIALS AND METHODS

Study area

Xiamen is a coastal city in southeast China (118°04′04″ E and 24°26′46″ N). The gross domestic product (GDP) of Xiamen reached 281.52 billion CNY in 2012, up from 55.83 billion CNY in 2001. The secondary and tertiary industries are the main economic sectors and represented 48.4% and 50.7% of industrial activity, respectively in 2012. The urbanization rate was 80.9% in 2012. The weather of Xiamen is dominated by a monsoonal humid subtropical climate with abundant rainfall. The total precipitation amounts to 1,144 mm, most of which falls between April and August. Water resources have been under critical pressure due to a lack of water availability, growing population, and economic development (Tang et al. 2013). During the period 2001 to 2012, the population expanded from 2.19 million to 3.67 million. Accordingly, the average per capita water resource decreased from 669.86 m³ in 2001 to 333.90 m³ per capita in 2012. The recent figure represents only 41% of the national level and is much lower than the internationally recognized minimum standard of 1,000 m³ per capita. The city was therefore listed as a ‘water-poor’ city by the Chinese National Ministry of Water Resources.

Methodology and data

The urban WF can be measured by the water production footprint (WFprod) and the water consumption footprint (WFcons), and a balance between the two can be reached by virtual water flows (Vanham & Bidoglio 2014). Both WFs represent four sectors: agriculture (including crops and livestock), industry, household water use, and commerce. In this paper, only the blue and green WF were quantified, while the grey WF was ignored since the agricultural pollution load data are unavailable and also due to the consequent unsureness concerning the environmental impact of its use (Chenoweth et al. 2013; Gu et al. 2014; Pfister & Ridoutt 2014). As shown below, WFprod and WFcons can be calculated by adding up the WF of each sector. Net imported virtual water (VWni)
is equal to \(WF_{\text{cons}}\) minus \(WF_{\text{prod}}\).

\[
WF_{\text{prod}} = WF_{\text{crops,prod}} + WF_{\text{livestock,prod}} \\
+ WF_{\text{industry,prod}} + WF_{\text{household,prod}} \\
+ WF_{\text{commerce,prod}} \tag{1}
\]

\[
WF_{\text{cons}} = WF_{\text{crops,cons}} + WF_{\text{livestock,cons}} \\
+ WF_{\text{industry,cons}} + WF_{\text{household,cons}} \\
+ WF_{\text{commerce,cons}} \tag{2}
\]

\[
VW_{ni} = WF_{\text{cons}} - WF_{\text{prod}} \tag{3}
\]

where \(WF_{\text{crops,prod}}\), \(WF_{\text{livestock,prod}}\), \(WF_{\text{industry,prod}}\), \(WF_{\text{commerce,prod}}\) represent the WF of crops, livestock, industry, and commerce respectively, from a production prospective (m\(^3\)/year). \(WF_{\text{crops,cons}}\), \(WF_{\text{livestock,cons}}\), \(WF_{\text{industry,cons}}\), \(WF_{\text{household,cons}}\) and \(WF_{\text{commerce,cons}}\) refers to the WF of crops, livestock, industry, household, and commerce respectively, from a consumption perspective (m\(^3\)/year).

**WF of crops**

The WF of crops is defined as water used by agricultural products in the periods of growth and harvest. The production and consumption WF of crops were calculated by the virtual water content of crops (\(VW_{\text{crops}}\), m\(^3\)/ton), which were formulated as follows.

\[
WF_{\text{crops,prod}} = \sum (VW_{\text{crops}}[i] \times P_{\text{crop}}[i]) \tag{4}
\]

\[
WF_{\text{crops,cons}} = \sum (VW_{\text{crops}}[i] \times C_{\text{crop}}[i]) \tag{5}
\]

\[
VW_{\text{crop,ni}} = WF_{\text{crops,cons}} - WF_{\text{crops,prod}} \tag{6}
\]

where \(P_{\text{crop}}[i]\) and \(C_{\text{crop}}[i]\) are the production (ton/year) and consumption (ton/year) of crop \(i\) in Xiamen, respectively. \(VW_{\text{crops}}[i]\) is the virtual water content of crop \(i\) production (m\(^3\)/ton), \(VWC_{\text{crops}}[i]\) is the virtual water content of crop \(i\) consumption (m\(^3\)/ton), and \(VW_{\text{crop,ni}}\) is the net imported virtual water of the crops sector (m\(^3\)/year).

The virtual water content of crop production (\(VWC_{\text{crops}}[i]\)) is equal to the local crop water requirement (CWR), which is calculated as the product of reference crop evapotranspiration and a corresponding crop coefficient. The CWR can be calculated by CROPWAT software developed by the Food and Agriculture Organization (Hoekstra et al. 2012). Data on climate, crop type, cultivation time, and soil conditions are required for the calculation. The formulas are as follows.

\[
VWC_{\text{crops}}[i] = \frac{CWR_{\text{crops}}[i]}{Y[i]} \tag{7}
\]

\[
CWR_{\text{crops}}[i] = ET_{\text{crop}}[i] \times 10 = K_{\text{crop}}[i] \times ET_0 \times 10 \tag{8}
\]

where \(VWC_{\text{crops}}[i]\) is virtual water content of crop \(i\) (m\(^3\)/ton), \(CWR\) is crop water requirement (m\(^3\)/ha) and \(Y[i]\) is the crop yield (ton/ha). \(ET_{\text{crop}}[i]\) is the crop evapotranspiration (mm) factor. The factor of 10 was used to convert the unit mm to m\(^3\)/ha. \(K_{\text{crop}}[i]\) is crop coefficient of crop \(i\) and \(ET_0\) is the reference crop evapotranspiration.

The virtual water content for crop consumption (\(VWC_{\text{crops}}\)) is the weighted average of local and imported virtual water content of crops according to local crops production and imported crops.

The calculation of this sector contained main crops, including grains, oil crops, vegetables, fruits, and tea. The data for the production and consumption of the crops, climate, crop types, cultivation times, and soil conditions were taken from the *Yearbook of Xiamen Special Economic Zone (2002–2013)* (Xiamen Bureau of Statistics 2002-2013).

**WF of livestock**

The WF of livestock (\(WF_{\text{livestock}}\)) is the consumptive water use for growing and processing feed; water provided for livestock drinking, cleaning, housing, and the like; and water used for the butchering and processing of livestock products (Chapagain & Hoekstra 2002), which is equal to the product of virtual water content of livestock and the corresponding production or consumption amounts.

\[
WF_{\text{livestock,prod}} = \sum (VWC_{\text{livestock}}[i] \times P_{\text{livestock}}[i]) \tag{9}
\]
The virtual water content of exports was calculated as a weighted average of local and national virtual industrial water content.

**WF of household use and commerce**

The WF of household use and commerce (WF$_{household}$ and WF$_{commerce}$) were considered as equal to water consumption of household use and commerce (Ercin et al. 2013; Vanham & Bidoglio 2014), for which WF$_{household, prod}$ = WF$_{household, cons}$ and WF$_{commerce, prod}$ = WF$_{commerce, cons}$. $WF_{household}$ included water supply for permanent and non-permanent residents (e.g. tourists). $WF_{commerce}$ included water consumed by hotels, commercial enterprises, restaurants, etc. These data were both taken from *Xiamen Water Resources Bulletin (2001–2012)* (Xiamen Bureau of Water Resources 2002-2015).

**RESULTS AND DISCUSSION**

**WF of Xiamen city**

For Xiamen city, the production WF (WF$_{prod}$) showed a relatively stable trend, averaging 881.75 Mm$^3$/year and floating between 815.32 Mm$^3$/year and 996.07 Mm$^3$/year during the research period (Figure 1). There was a significant decrease of WF$_{prod}$ in 2007, which may reflect the local pork production decline caused by market conditions and policy (Xiamen Municipal Government 2006a, 2006b). The consumption WF (WF$_{cons}$), however, increased rapidly from 979.56 Mm$^3$/year in 2001 to 1,664.97 Mm$^3$/year in 2012 (Figure 2). Among the sectors, the average WF$_{livestock}$ accounted for the largest proportion of both WF$_{prod}$.
(40.95%) and \( \text{WF}_{\text{cons}} \) (48.74%) during the period. It was followed by \( \text{WF}_{\text{crops}} \) (19.06% for \( \text{WF}_{\text{prod}} \) and 29.54% for \( \text{WF}_{\text{cons}} \)), \( \text{WF}_{\text{industry}} \) (19.13% for \( \text{WF}_{\text{prod}} \) and 8.92% for \( \text{WF}_{\text{cons}} \)), \( \text{WF}_{\text{household}} \) (16.07% for \( \text{WF}_{\text{prod}} \) and 9.90% for \( \text{WF}_{\text{cons}} \)), and \( \text{WF}_{\text{commerce}} \) (4.79% for \( \text{WF}_{\text{prod}} \) and 2.90% for \( \text{WF}_{\text{cons}} \)).

**WF of agricultural products**

As already noted, the WF of agriculture (\( \text{WF}_{\text{agriculture}} \)), including the WF of crops and livestock, accounted for 60.01% and 78.28% of total WF from production and consumption perspectives, respectively, in Xiamen city (Figures 3 and 4). \( \text{WF}_{\text{agriculture}} \) for production decreased from 548.64 Mm\(^3\)/year in 2001 to 426.15 Mm\(^3\)/year in 2012; this decrease was caused by industrial adjustments and agricultural production technology improvements. The \( \text{WF}_{\text{agriculture}} \) of consumption, however, increased from 720.62 Mm\(^3\)/year to 1,345.32 Mm\(^3\)/year in that period; this increase was caused mainly by population growth.

Among the agricultural sectors, pork contributed most to the total agricultural WF from both production (35.63% of total WF) and consumption (32.18% of total WF) perspectives (Figures 3 and 4). It was followed by vegetable (8.95% of total) and grain (5.52% of total) in terms of production, and by grain (18.88% of total) and chicken meat (6.59% of total) in terms of consumption.

Comparing the WF for agricultural products between rural and urban areas, Figure 5 shows that urban residents consume more vegetables, fruit, and pork, but less grain than rural residents. Since pork is much more water intensive than grain, the WF of urban areas is higher than that of rural areas. This also indicated that diet changes when rural residents migrate to cities such as Xiamen. Against the background of rapid urbanization in Xiamen, there might be a significant growth in WF due to this change in diet. Some studies have suggested that WF can vary with dietary patterns (Vanham & Bidoglio 2014). In addition, urbanization is a significant driver for food waste (Parfitt et al. 2010), which may also lead to increasing WF.
Water efficiency in Xiamen city

To evaluate the efficiency of water production activity, per GDP WF of production $WF_{prod}$ was calculated by sector (agriculture, industry, and commerce). As shown in Figure 6, the value of WF per GDP by sector was normalized by subtracting the minimum and then dividing by the maximum range of the relevant sector. $WF_{prod}$ per GDP of industry and commerce both showed a significant decline from 2001 to 2012, decreasing by 69.86% and 52.95%, respectively. $WF_{prod}$ per GDP of agriculture decreased by only 16.64%, and actually increased from 2001 to 2006. The average per GDP WF of agriculture, which was 248.96 $m^3/10^3$ CNY, was much higher than those of industry (2.76 $m^3/10^3$ CNY) and commerce (0.69 $m^3/10^3$ CNY). Since the area of farmland served by efficient irrigation (mainly sprinkler and low-pressure drip irrigation) was only 38.37% in 2012, technology-driven improvements in irrigation have a large potential for water conservation in Xiamen.

Per capita consumption WF was also calculated to evaluate citizen consumption levels from 2001 to 2012. This coefficient shows a relatively stable trend during the study period, ranging from 440.28 $m^3/capita/year$ to 539.89 $m^3/capita/year$. The value of per capita WF in 2007 (495.25 $m^3/cap/year$) was lower than those of Fujian Province (717.27 $m^3/cap/year$) and China as a whole (648.11 $m^3/cap/year$) (Ge et al. 2014). To keep the calculation boundary coincident with later research, grey WF was included in the calculation. The low water consumption of Xiamen might reflect higher local production water efficiency because its main agricultural products were consumed locally.

Water conservation from trade

To understand the dependency on water trade, the balance of WF between production and consumption is shown in Figure 7. It shows that the gap between the consumption WF and the production WF increased greatly from 2001 to 2012 in Xiamen city, reaching 842.33 $Mm^3/year$ in 2012. This indicates that Xiamen was a net virtual water importer from 2001, satisfying its water needs by a virtual water trade. Figure 8 displays the contribution of net imported virtual water ($VW_{ni}$) for crops, livestock, and industry from 2001 to 2012. The livestock sector contributed most to the total $VW_{ni}$, the average proportion of which for total $VW_{ni}$ was 62.79%; its largest share coming from pork’s $VW_{ni}$ value of 147.00 $Mm^3/year$; this was followed by poultry (75.40 $Mm^3/year$), beef (43.69 $Mm^3/year$), eggs (41.77 $Mm^3/year$), and other animal products on average. Among crops, grain (216.38 $Mm^3/year$) and fruit (38.39 $Mm^3/year$) showed the most significant water
saving; in terms of vegetables, Xiamen was a net virtual water exporter (37.61 Mm³/year).

As Xiamen city has been short of land for agriculture, importing crops and livestock products to meet local demand could help reduce both water consumption and water pollution from agriculture. Although it may be considered as a strategy for water conservation, trade is always driven by factors other than water. Only when water availability is below a certain threshold can the link between per capita water resource availability and food imports be established (Yang et al. 2003).

CONCLUSIONS

To understand the current water situation in Xiamen city, the WFs from production and consumption perspectives were evaluated from 2001 to 2012. The efficiency of the WF and the dependency on outside sources were also presented in this paper. Our main conclusions are as follows.

(1) From a production perspective, the WF of Xiamen city was 881.75 Mm³ on average and showed a relatively stable trend. The consumption WF, however, increased from 979.56 Mm³/year in 2001 to 1,664.97 Mm³/year in 2012. Livestock contributed most to the WF of production and consumption; it was followed by crops, industry, household use, and commerce.

(2) Agriculture was the largest sector in terms of WF, and pork contributed most to the WF of agriculture from production and consumption perspectives. There was a difference in the agriculture consumption WF between urban and rural areas due to different diet structures; urban residents consume more water-intensive products, such as pork and fruit, rather than less water-intensive products such as grain.

(3) On average, the per-GDP WF of agriculture (248.96 m³/10³ CNY) was much higher than those of industry (2.76 m³/10³ CNY) and commerce (0.69 m³/10³ CNY). The latter two decreased by 69.82% and 52.95%, respectively, during the study period, while that of agriculture dropped by only 16.64%. The per capita WF in Xiamen city averaged 482.48 m³/year and remained relatively stable.

(4) In terms of virtual water trade balance, water resources have been conserved by Xiamen city, in which the net imported virtual water increased from 2001. Among the sectors, livestock was the largest contributor to net imported virtual water (338.25 Mm³/year); it was followed by crops (248.03 Mm³/year). Xiamen was a net exporter, however, in terms of industrial virtual water trade (47.59 Mm³/year).

In the future, we expect significant growth in the consumption WF due to population growth, economic development, and changes in resident diet pattern. To solve the water shortage in Xiamen city, the main measures lie in improving the efficiency of water production, decreasing per capita consumption WF, and importing more virtual water through trade. For improving the efficiency of water production, water conservation measures must be adopted in each sector and the industrial structure must be adjusted to become less water intensive. Irrigation improvement in Xiamen has a large potential for water conservation, which would improve the efficiency of water production. To decrease the per capita water consumption footprint, a balanced and healthy diet should be promoted, especially in terms of reducing food waste. Finally, Xiamen should strengthen its trade links to areas with abundant water resources and increase its imports of virtual water; this would reduce stress on local water resources, especially those used for water-intensive agricultural products.

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