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Assessing regional virtual water flows and water footprints in the Yellow River Basin, China: A consumption based approach

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ABSTRACT

The Yellow River, the second longest river in China, is facing increasing water scarcity due to rising water consumption of a fast growing economy and an increasingly urbanized population with water-intensive consumption patterns. The Yellow River Basin (YRB) is divided into three regions: the upper, middle and lower reaches; each with very different characteristics in terms of water resources, economic structure and household income and consumption patterns. Virtual water has been recognised as a potentially useful concept for redistributing water from water-rich to water-poor regions. In this study, we develop a Multi-Regional Input–Output model (MRIO) to assess the regional virtual water flows between the three reaches of the basin and the rest of China distinguishing green and blue water, as well as rural and urban household water footprints. Results show that all three reaches are net virtual water exporter, i.e. production and consumption activities outside the basin also put pressure on the water resources in the YRB. The results suggest a reduction of the export of virtual blue water that could instead be used for producing higher value added but lower water-intensive goods. In particular, the lower reach as the most water scarce region in the basin should increase the import of water intensive goods, such as irrigated crops and processed food products, from other more water abundant regions such as the South of China. Thus, trading virtual water can help sustain the economic growth of the regions within the basin thus easing the pressure from water shortage. In addition, there is a huge gap between urban and rural household water footprints in the basin. The average urban household's water footprint is more than double the water footprint of a rural household in the basin. This is due to the higher urban household consumption of water-intensive goods and services, such as processed food products, wearing apparel and footwear, hotel and catering services and electricity.

Introduction

The Yellow River, the second longest river in China, flows over 5400 km and runs through 9 provinces including Qinghai, Sichuan, Gansu, Ningxia, Inner-Mongolia, Shanxi, Shannxi, Henan and Shandong (see Fig. 1). The total area of the Yellow River Basin (YRB) is 795 thousand km^2, about 8.2 percent of China's total area (YRCC, 2007). As "cradle of Chinese Civilization", the basin played a significant role in China's long history and economic development (Zhu, Giordano, Cai, & Molden, 2004). The YRB is commonly divided into three regions: the upper, middle and lower reaches (see Fig. 1). Each section of the river shows very different characteristics in terms of water resources, economic structure, and household incomes and consumption patterns. The YRB has been facing increasing water demand due to a fast growing and changing economy and changing lifestyles. Through trade of goods and services in interdependent regional economies, the consumption in each region is linked to water consumption in other regions between the three reaches in the YRB and the rest of China. Governmental strategies on sustainable water management solely focus on regional domestic water consumption mainly through supply-side and efficiency measures largely ignoring the potential for demand side management. However, inhabitants of a region not only cause water consumption in their own region but beyond through the consumption of imported commodities. To diminish water scarcity, it is crucial to take the main water consumers inside and outside the region through regional trade into account, particularly for a water scarce region like the YRB exporting water-

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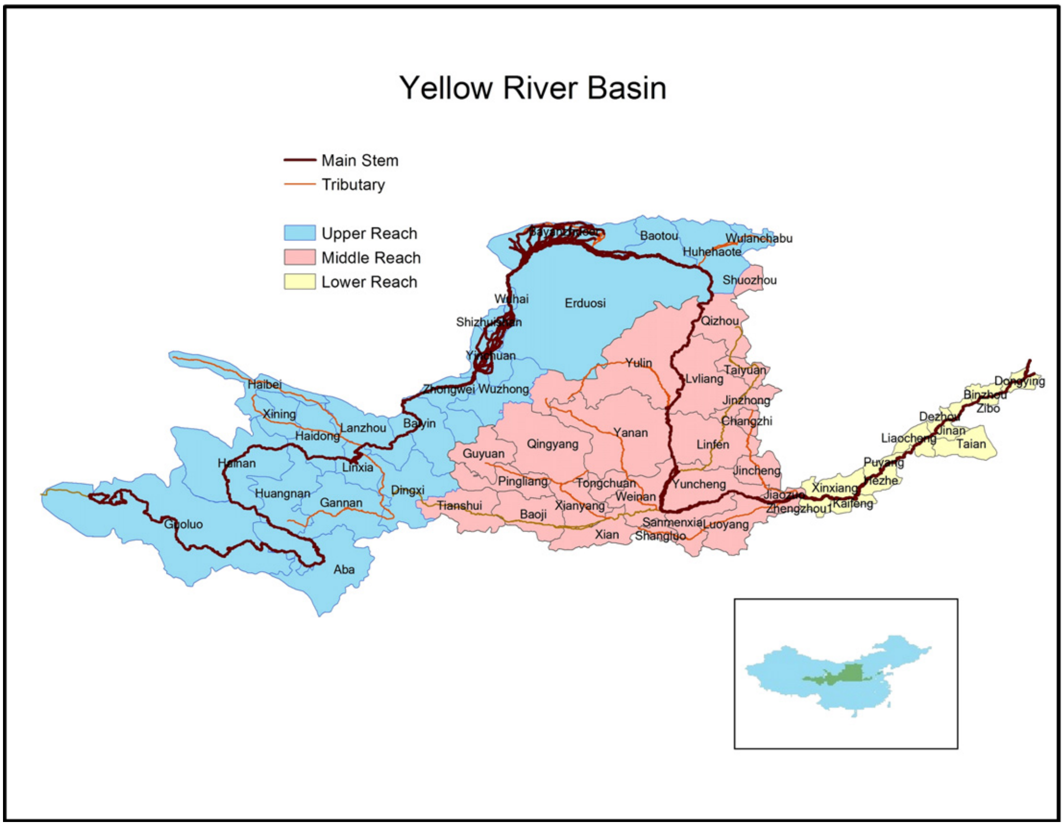

Fig. 1. The three reaches of the Yellow River Basin.

intensive goods to other regions. In this paper, we aim to develop a multi-regional input–output accounting framework to assess the regional virtual water flows (both green and blue water) between the three reaches of the Yellow River Basin and the rest of China, and to calculate water footprints for rural and urban households in each part of the basin.

The concept of virtual water was first introduced by Allan (1998) to describe the total volume of water embedded in agricultural products suggesting that water poor regions should import water intensive agricultural products. A number of studies have recognized the usefulness of the concept of virtual water for analysing production patterns and associated water flows (e.g. Dietzenbacher & Velázquez, 2007; Zeitoun, Allan, & Mohieldeen, 2010). A closely related concept in the literature is the water footprint (WF), which is the total virtual water content of products consumed by an individual, business, town, city or country (Chapagain & Orr, 2009). The water footprint as a consumption-based environmental indicator was initially introduced by Hoekstra and Hung (2002) as analogy to the 'ecological footprint', but had frequently been used before in the input–output literature (e.g. Carter & Ireri, 1970; Lange, 1998). Several studies have distinguished between 'green' and 'blue' components of virtual water (Chapagain, Hoekstra, Savenije, & Gautam, 2006; Jewitt, 2006; Rost et al., 2008; Yang, Wang, Abbaspour, & Zehnder, 2006; Yang & Zehnder, 2007). "Green water" is the effective rainfall or soil moisture that is used directly by plants, and "blue water" is surface and ground water (WFN, 2008; Wichelns, 2010), where green water is exclusively important for agricultural sectors; blue water has wider applications throughout the economy and especially high value added production activities (Chapagain et al., 2006; Wichelns, 2004, 2010).

The water is consumed not only directly in the production of goods and services, but also indirectly by using other goods and services as inputs and their respective virtual water. The water footprint based on environmental input–output analysis (EIOA), can be used as a means to identify the 'hidden' water consumers along the whole supply chain and for balancing supply and demand of water resources in water scarce regions (Hubacek, Guan, Barrett, & Wiedmann, 2009) such as the Yellow River Basin. This consumption-based approach has been frequently used for calculating consumption-based inventories for greenhouse gases emissions (see for example Davis & Caldeira, 2010).

Environmental input–output analysis (EIOA) has been applied to assess virtual water flows and water footprints in many studies (e.g. Cazcarro, Pac, & Sánchez-Chóliz, 2010; Feng et al., 2011; Hubacek et al., 2009; Hubacek & Sun, 2005; Madrid, Hoekstra, & Alcantara, 2008; Wang & Wang, 2009; Yu, Hubacek, Feng, & Guan, 2010; Zhao, Chen, & Yang, 2009). As a typical top-down approach, EIOA offers a variety of appealing features for water footprinting. First, the approach provides a complete description of the regional and/or inter-regional supply chain and avoids the truncation error typically encountered for bottom-up approaches, such as process analysis and the virtual water approach (Feng et al., 2011). Second, EIOA approaches assign the water to final rather than intermediate consumption, which allows us assessing both direct and indirect water requirements of final consumption pattern of a nation, region, a lifestyle group or a household. Two limitations of applying EIOA approach to water footprinting need to be pointed out: One is the general aggregation issue at the level of economic sectors rather than individual products, particularly for agricultural sectors which are highly interesting for the water footprint analysis. To solve this issue, for each region we further look at a number of crops more specifically, in terms of water requirement, irrigation rate, sown areas and crops productivity. The second shortcoming is the domestic technology assumption because limited data is available on inter-linkages between different regions or countries. In most input–output studies, the technology outside the country is assumed to be produced with the same technology mix as the domestic production. To overcome this assumption, we apply a multi-regional input–output model to calculate the water footprint in the YRB.

Geographical and socio-economic characteristics of the YRB

The population of YRB in 2007 was around 114 million or 9 percent of the total population in China, more than twice the population of 1950. Urbanization rate in YRB was 39 percent, about 13 percent lower than China's national average. In 2007, the Gross Domestic Product (GDP) of the YRB was 2112 billion Yuan, accounting for about 8 percent of China's total GDP (National Statistical Bureau of China, 2008a). In the basin and its flood plains, crop production contributed 16.2 percent of China's national total (Zhu et al., 2003b).

The three reaches in the YRB are shown in Fig. 1. The upper reach begins from the origin of Yellow River in the Bayangela Mountains, Qinghai province, to Hekouzhen gauging station, and drains over half of the total basin area. Low evaporation and high moisture retention combined with high precipitation levels, result in the upper reach contributing 54 percent of the basin's water resources (YRCC, 2007). The upper reach is located in western China which has relatively low population densities (about 70 persons/km^2), higher dependence on agriculture and low industrialization levels (Zhu et al., 2004). Agricultural activities consume a huge amount of water in this region, around 93 percent of the regional total water consumption (YRCC, 2007). The middle reach commences at Hekouzhen gauging station. From there, the river begins its southward route and cuts through the Loess Plateau which is considered the world's most erodible land surface (Zhu et al., 2003b). In the middle reach, large amounts of Loess soil enter the river's main stream and tributaries resulting in high sediment concentration where its name "Yellow" derives (Giordano et al., 2004). The middle reach covers 46 percent of the basin and supplies 35 percent of the total water resources. It plays a significant role in the river's availability for human use as it constitutes some of Yellow River's major tributaries such as the Fen River and the Wen River (YRCC, 2004). The increase of irrigation areas and growing industrial activities substantially increases water depletion. The middle reach lies between west and central China, which covers most areas of Shannxi province and Shanxi province, and a small part of Henan province. The middle reach has a relatively high population density (around 210 persons/km^2). Arid climate and decreasing water resources limit agriculture development in this part of the river basin (Zhu et al., 2003b). However, it has the largest coal deposits in China, particularly the Shanxi province which is a leading producer of coal with annual production exceeding 300 million metric tonnes (State Statistical Bureau of China, 2004). The lower reach begins at Huayuankou and then continues east to its terminus in the Bohai Gulf. The lower reach only contributes 11 percent of the basin's water resources, has highest population density (about 750 persons/km^2) and GDP per capita in the YRB and lowest water availability per person. In the lower reach, the water consumption by local production activities has already exceeded the total local water resources. Thus, the region faces serious water scarcity and significantly relies on water inflows from the upper and middle reaches. The detailed information is shown in Table 1.

Methodology

To quantify the virtual water flows (embedded water in goods and services) between the reaches in the Yellow River Basin and the rest of China, we apply a multi-regional input–output economic and water accounting framework. This allows us to depict and assess the domestic and total water footprints at sector level for each region and for rural and urban households. In this study, the domestic water footprint is defined as the domestic water resources consumed by local production and consumption activities in a region; and the total water footprint is the total amount of water consumed from local and national water resources to satisfy domestic final demand in a region.

Basic input–output model

Input–output analysis is an analytical framework developed by Wassily Leontief in the late 1930s (Miller & Blair, 2009) and has been subsequently further developed and applied in a large number of studies. The mathematical structure of an input–output system consisting of *n* linear equations is shown in Eq. (1). The equation depicts how the production of an economy depends on intersectoral relations and final demand.

$$\begin{aligned} x_1 &= Z_{11} + Z_{12} + \cdots + Z_{1n} + y_1 \\ x_2 &= Z_{21} + Z_{22} + \cdots + Z_{2n} + y_2 \\ \vdots & \qquad \vdots \qquad\qquad \vdots \\ x_n &= Z_{n1} + Z_{n2} + \cdots + Z_{nn} + y_n \end{aligned} \tag{1}$$

Eq. (1) can be re-written as in Eq. (2).

$$x_i = \sum_{j=1}^{n} Z_{ij} + y_i \tag{2}$$

Table 1
Geographical and socio-economic characteristics of the YRB in 2007.

		Upper	Middle	Lower	Whole basin
Drain Area (thousand km^2)		428	343	24	794
Sown area (thousand hectare)		4982	5773	1933	12,531
Irrigation land (thousand hectare)		1786	1935	837	4424
Population (million)		30	72	18	114
Population density (persons/km^2)		70	210	750	230
Urbanization rate (%)		39	35	50	39
GDP per capita (Yuan)		21,868	19,064	23,853	19,725
Precipitation (million m^3)		164,100	191,700	29,100	384,900
Water resources[a] (million m^3)		35,274	22,902	7354	65,530
Water consumption (million m^3)	Irrigation	10,650	7417	7965	26,032
	Livestock, forestry and fishery	1558	808	615	2981
	Industry	1426	2038	719	4183
	Services	187	366	144	697

Data source: China Provincial Statistical Yearbooks 2008, YRCC 2007.
[a] Water resource comprises surface and ground water resources from local precipitation. It excludes the water inflows from other regions.

Where n is the number of economic sectors of an economy; x represents the total economic output of the i^{th} sector; y_i is the final demand of sector i. z_{ij} represents the monetary flows from the i^{th} sector to the j^{th} sector. Technical coefficient a_{ij}, is derived by dividing the inter-sectoral flows from i to $j(z_{ij})$ by total input of sector $j(x_j)$,

$$a_{ij} = z_{ij}/x_j \tag{3}$$

By substituting Eq. (3) to (2), the following equation is derived.

$$x_i = \sum_{j=1}^{n} a_{ij}x_j + y_i \tag{4}$$

Eq. (4) can be written in form of matrix as below.

$$x = Ax + y \tag{5}$$

Where A is the coefficient matrix; *x* is a vector of sectoral output; *y* is a vector of final demand.

To solve for x, we get

$$x = (I - A)^{-1}y \tag{6}$$

where $(I–A)^{-1}$ is known as the Leontief inverse matrix which shows the total production required to satisfy one unit of final demand in the economy.

Multi-regional input–output model (MRIO)

In this study we build a four-region MRIO accounting framework: upper reach, middle reach, lower reach and the rest of China. The interconnections among the regions in the multi-regional input–output model are captured from the interregional shipment of commodities.

For sector i, let z_i^{PQ} denotes the monetary flow of good i from region P (shipping region) to region Q (receiving region), irrespective of the sector of destination in the receiving region. These flows will include shipments to the producing sectors in region Q and to final demand in region Q. Thus, for each sector there is a shipments matrix shown in Table 2, where U, M, L and R denote upper reach, middle reach, lower reach and rest of China. Each column sums in Table 2 represents the total shipments of good i into that region from all of the regions in the model. For the column *upper*, the total is denoted by T_i^U:

$$T_i^U = z_i^{UU} + z_i^{MU} + Z_i^{LU} + z_i^{RU} \tag{7}$$

If each element in column *upper reach* is divided by this total, we have coefficient denoting the proportion of all of good *i* used in *upper reach* that comes from each of four regions. These proportions are denoted by t_i^{UU}, t_i^{MU}, t_i^{LU} and t_i^{RU}:

$$t_i^{UU} = \frac{z_i^{UU}}{T_i^U}, \quad t_i^{MU} = \frac{z_i^{MU}}{T_i^U}, \quad t_i^{LU} = \frac{z_i^{LU}}{T_i^U} \quad \text{and} \quad t_i^{RU} = \frac{z_i^{RU}}{T_i^U} \tag{8}$$

Therefore, the shipment data in Table 2 can be re-written in terms of these proportions shown in Table 3:

For each possible origin–destination pair of regions, denoted by t^{PQ}.

$$t^{PQ} = \begin{bmatrix} t_1^{PQ} \\ \vdots \\ t_n^{PQ} \end{bmatrix}$$

The *n*-element column vector (t^{PQ}) shows the proportion of the total amount of each good used in region *q* that comes from region P. We then construct T^{PQ}:

$$T^{PQ} = \begin{bmatrix} t_1^{PQ} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & t_n^{PQ} \end{bmatrix}$$

$$\text{Let}\, A^* = \begin{bmatrix} A^U & 0 & 0 & 0 \\ 0 & A^M & 0 & 0 \\ 0 & 0 & A^L & 0 \\ 0 & 0 & 0 & A^R \end{bmatrix}, T = \begin{bmatrix} T^{UU} & T^{UM} & T^{UL} & T^{UR} \\ T^{MU} & T^{MM} & T^{ML} & T^{MR} \\ T^{LU} & T^{LM} & T^{LL} & T^{LR} \\ T^{RU} & T^{RM} & T^{RL} & T^{RR} \end{bmatrix}, X^* = \begin{bmatrix} x^U \\ x^M \\ x^L \\ x^R \end{bmatrix},$$

$$\text{and}\; y^* = \begin{bmatrix} y^U \\ y^M \\ y^L \\ y^R \end{bmatrix}$$

where A^*, x^* and y^*denote compound regional technical coefficients matrices, total output and final demand for upper reach (U), middle reach (M), lower reach (L) and rest of China (R), respectively. Then, the compound statement of the basic accounting relations in a four region MRIO model is seen to be:

$$x^* = TA^*x^* + Ty^* \tag{9}$$

so that Eq. (9) can be re-arranged as:

$$\left(I - TA^*\right)x^* = Ty \tag{10}$$

and the solution will be given by

$$x^* = \left(I - TA^*\right)^{-1}Ty^* \tag{11}$$

Virtual water flows and water footprints

We extend the MRIO model by adding a row vector of direct water consumption coefficients in physical unit for the four regions. The direct water consumption coefficient f_j^U is calculated by dividing the total amount of water directly consumed in the j^{th} sector by the total sector input in the upper reach, which represents the share of water consumption per unit of output in sector j. Thus, a row vector of compound water consumption coefficient is shown by:

$$f^* = \begin{bmatrix} f^U & f^M & f^L & f^R \end{bmatrix}$$

Table 2
Interregional shipment of commodity *i.*

Shipping region	Receiving region			
	Upper reach	Middle reach	Lower reach	Rest of China
Upper reach	z_i^{UU}	z_i^{UM}	z_i^{UL}	z_i^{UR}
Middle reach	z_i^{MU}	z_i^{MM}	z_i^{ML}	z_i^{MR}
Lower reach	z_i^{LU}	z_i^{LM}	z_i^{LL}	z_i^{LR}
Rest of China	z_i^{RU}	z_i^{RM}	z_i^{RL}	z_i^{RR}
Total	T_i^U	T_i^M	T_i^L	T_i^R

Table 3
Proportion of interregional shipment of commodity *i.*

Shipping region	Receiving region			
	Upper reach	Middle reach	Lower reach	Rest of China
Upper reach	t_i^{UU}	t_i^{UM}	t_i^{UL}	t_i^{UR}
Middle reach	t_i^{MU}	t_i^{MM}	t_i^{ML}	t_i^{MR}
Lower reach	t_i^{LU}	t_i^{LM}	t_i^{LL}	t_i^{LR}
Rest of China	t_i^{RU}	t_i^{RM}	t_i^{RL}	t_i^{RR}
Total	1	1	1	1

where f^U, f^M, f^L and f^R denote the direct water consumption coefficients of each region.

Calculating virtual water flows

In this section, we quantify the virtual water flows among the four study regions. Here, we use the upper reach as an example to illustrate how to calculate the regional virtual water flows based on water extended MRIO model. For convenience, the term of $(I-TA^*)^{-1}$ is written as L^* and Ty^* as y^{U*}. The elements of L^* and y^{U*} are shown as:

$$L^* = \begin{bmatrix} L^{UU} & L^{UM} & L^{UL} & L^{UR} \\ L^{MU} & L^{MM} & L^{ML} & L^{MR} \\ L^{LU} & L^{LM} & L^{LL} & L^{LR} \\ L^{RU} & L^{RM} & L^{RL} & L^{RR} \end{bmatrix} \text{ and } y^{U*} = \begin{bmatrix} y^{UU} \\ y^{MU} \\ y^{LU} \\ y^{RU} \end{bmatrix}$$

Each element in L^* shows the total inputs required from shipping region to fulfil one unit of final demand. Each element in y^{U*} shows the goods produced in the shipping region directly consumed by the upper reach's final consumers.

The virtual water imported from the shipping region are consumed directly and indirectly in order to satisfy the final demand in the receiving region. As we want to capture the virtual water imported from a specific shipping region to the upper reach, f^{U*}, f^{M*}, f^{L*} and f^{R*} only contain the water consumption coefficients for the target region with zeros for the rest of regions.

$$f^{U*} = \begin{bmatrix} f^U & 0 & 0 & 0 \end{bmatrix}, f^{M*} = \begin{bmatrix} 0 & f^M & 0 & 0 \end{bmatrix}, f^{L*} = \begin{bmatrix} 0 & 0 & f^L & 0 \end{bmatrix},$$
$$\text{and } f^{R*} = \begin{bmatrix} 0 & 0 & 0 & f^R \end{bmatrix}$$

For the upper reach, the total virtual water inflow from middle reach, lower reach and Rest of China can be calculated by:

$$\begin{aligned} VF^{MU} &= f^{M*}L^*y^{U*} = f^M L^{MU} y^{UU} + f^M L^{MM} y^{MU} + f^M L^{ML} y^{LU} + f^M L^{MR} y^{RU} \\ VF^{LU} &= f^{L*}L^*y^{U*} = f^L L^{LU} y^{UU} + f^L L^{LL} y^{LU} + f^L L^{LM} y^{MU} + f^L L^{LR} y^{RU} \\ VF^{RU} &= f^{R*}L^*y^{U*} = f^R L^{RU} y^{UU} + f^R L^{RR} y^{RU} + f^R L^{RM} y^{MU} + f^R L^{RL} y^{LU} \end{aligned} \quad (12)$$

In Eq. (12), VF^{MU} represents the virtual water inflow from the middle reach. $f^M L^{MU} y^{UU}$ captures the virtual water imported from the middle reach for the upper reach's intermediate use; $f^M L^{MU} y^{MU}$ captures the virtual water imported from the middle reach for the upper reach's final use; $f^M L^{ML} y^{LU}$ is the virtual water imported from middle reach by lower reach's intermediate use for the upper reach's final use; $f^M L^{MR} y^{RU}$ captures the virtual water imported from middle reach by the rest of China's intermediate use for the upper reach's final use. Analagous explanations can be applied to VF^{LU} and VF^{RU}

Therefore, the total virtual water flows to the upper reach from all other regions can be calculated by

$$VF^U = VF^{MU} + VF^{LU} + VF^{RU} \quad (13)$$

Calculating water footprints

This section illustrates how to calculate regional domestic and total water footprints, where total water footprints include rural and urban household water footprints, based on the MRIO framework. To calculate regional domestic and total water footprints, it is important to identify the domestic and total water multipliers which are used to assess supply chain effects of the direct and indirect water consumption to satisfy one monetary unit of final demand. Domestic water multipliers can be denoted by:

$$\begin{aligned} M^U_{Dom} &= f^U\left(I - A^U_{Dom}\right)^{-1} \\ M^M_{Dom} &= f^M\left(I - A^M_{Dom}\right)^{-1} \\ M^L_{Dom} &= f^L\left(I - A^L_{Dom}\right)^{-1} \\ M^R_{Dom} &= f^R\left(I - A^R_{Dom}\right)^{-1} \end{aligned} \quad (14)$$

where M^U_{Dom}, M^M_{Dom}, M^L_{Dom} and M^R_{Dom} are domestic water multiplier for upper reach, middle reach, lower reach and Rest of China; $A^U_{Dom}A^M_{Dom}A^L_{Dom}$ and A^R_{Dom} denote domestic technical coefficients for the four studying regions. And total water multiplier can be calculated by:

$$M_{tot} = f^* L^* \quad (15)$$

where M_{tot} is a row vector of containing sectoral level total water multiplier for the four study regions.

Domestic water footprints are the total water consumed from regional domestic water resource for the total final demand (both domestic final demand and export) in a region. Regional domestic water footprints are calculated by:

$$\begin{aligned} w^U_{Dom} &= M^U_{Dom}(y^U + e^U) + w^U_{hh} \\ w^M_{Dom} &= M^M_{Dom}(y^M + e^M) + w^M_{hh} \\ w^L_{Dom} &= M^L_{Dom}(y^L + e^L) + w^L_{hh} \\ w^R_{Dom} &= M^R_{Dom}(y^R + e^R) + w^R_{hh} \end{aligned} \quad (16)$$

Where w^U_{Dom}, w^M_{Dom}, w^L_{Dom} and w^R_{Dom} denotes domestic water footprints for upper reach (upper case U), middle reach (upper case M), lower reach (upper case L) and Rest of China (upper case R); y^U, y^M, y^L and y^R are regional domestic final demand of the four regions; e^U, e^M, e^L and e^R are exports of the four regions; w^U_{hh}, w^M_{hh}, w^L_{hh} and w^R_{hh} denote the direct household water consumption.

Total water footprints are the total water consumption from all water resources to satisfy the regional domestic final demand. Therefore, people living in the region are not only responsible for the water consumed from their domestic water resource, but also the water from other regions' water resources required by their final consumption. The total water footprints for the upper reach can be captured by:

$$\begin{aligned} w^U_{Tot} &= M_{tot} y^{U*} + w^U_{hh} \\ &= f^U L^{UU} y^{UU} + f^U L^{UM} y^{MU} + f^U L^{UL} y^{LU} + f^U L^{UR} y^{RU} \\ &\quad + VF^{MU} + VF^{LU} + VF^{RU} + w^U_{hh} \end{aligned} \quad (17)$$

where w^U_{Tot} is the row vector of total water footprint for the upper reach; $f^U L^{UU} y^{UU}$ is used for capturing the upper reach's virtual water flows within the region, $f^U L^{UM} y^{MU}$, $f^U L^{UL} y^{LU}$ and $f^U L^{UR} y^{RU}$ are that the virtual water from upper reach exported to middle, lower reach and Rest of China consumed by upper reach's domestic final consumers by interregional trade; VF^{MU}, VF^{LU} and VF^{RU} are upper reach's imported virtual water from other three region's domestic water resources. Total water footprints for middle reach, lower reach and rest of China can be calculated by Eq. (18).

$$\begin{aligned} w_{Tot}^{M} &= M_{tot}y^{M*} + w_{hh}^{M} \\ w_{Tot}^{L} &= M_{tot}y^{L*} + w_{hh}^{L} \\ w_{Tot}^{R} &= M_{tot}y^{R*} + w_{hh}^{R} \end{aligned} \quad (18)$$

where y^{M*}, y^{L*} and y^{R*} are domestic final demand of middle reach, lower reach and Rest of China similar as y^{U*} in Eq. (17).

Data

As the Yellow River passes through nine provinces, the watershed of Yellow River does not align with the administrative boundaries of China. However, any data in China's official statistical database, which are collected from local governments, are generally defined in terms of administrative boundaries. In order to analyse the water consumption and socio-economic activities within the YRB, administrative boundaries need to be aligned with the watershed. In this study, two types of GIS databases are used; namely, the county level of administrative boundaries GIS database and the Yellow River watershed GIS dataset which contains the Yellow River main stream and its tributaries. Fig. 2 shows the hierarchical system of China's administrative boundaries. In this study, we match the watershed with the administrative boundaries at the county level which is the most detailed GIS database we have. The counties that fall into the watershed of the YRB are identified. Although the administrative boundaries at county level are not exactly matching the watershed boundaries, they still provide a good proxy. Fig. 1 depicts the administrative boundaries in the watershed of the YRB and the main stream and tributaries of the Yellow River. The GIS database for administrative boundaries and the watershed of the YRB are collected from the National Fundamental Geographic Information System of China (NFGIS, 2003).

This study constructs four regional input–output tables which are used for the MRIO model. Three methods to construct IO table are frequently used in the literature: survey based, semi-survey and non-survey techniques (Miller & Blair, 2009). The survey based and semi-survey approaches have high accuracy but at high cost and are time consuming (Miller & Blair, 2009). The non-survey approach commonly applied the Location Quotient technique using detailed sectoral economic data such as labour data or value added to adjust the technical coefficients to reflect the actual size of the respective section within the study region. However, these data are not available at county level in the YRB. A scaling method which is based on proportional spatial distribution is applied to the 2007 provincial IO tables by using the total economic output of aggregated agriculture, industry, construction and service sector in the identified counties. Then, we merge the adjusted provincial IO tables in each reach to create three regional IO tables for the YRB. The rest of China IO table are obtained from China's national table by removing the three region's intermediate and final demands in the YRB.

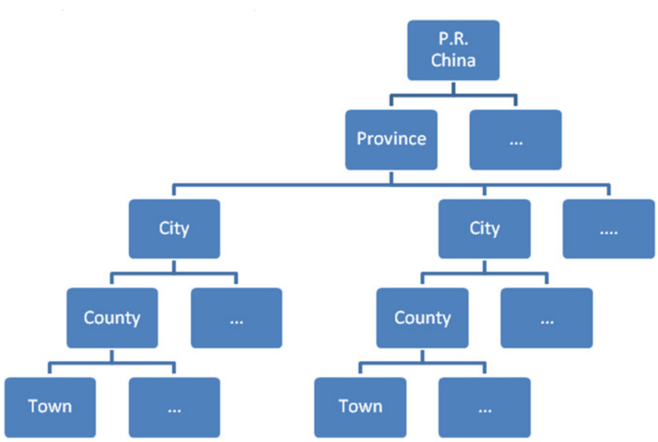

Fig. 2. The hierarchy of China's administrative boundaries.

The 2007 IO tables (48 by 48 sectors) for the nine provinces are collected and aggregated from the National Statistical Bureau of China. The input–output tables include 5 agriculture sectors, 29 industry sectors and 14 service sectors, where the detailed agricultural sectors are including Crops, Livestock, Forestry, Fishery and Agricultural services. Based on regional rail transportation data, the regional trade coefficients are estimated by using a gravity model, which was initially developed by Leontief and Strout (1963) in an input–output context (Detailed description of the gravity approach can be found in Miller & Blair, 2009). The rail transportation data are collected from China Transport Statistical Yearbook (National Statistical Bureau of China, 2008b). Given that rail transport is the only data currently available in terms of regional trade flows, we have to assume that road and water transport have the same regional percentage share of trade as the rail transport. Finally, the blue water consumption data by sectors (irrigation, livestock, industry, service sectors) are collected from the Yellow River Water Resources Bulletins published by the Yellow River Conservancy Commission (YRCC) (YRCC, 2007). The industry and service sectors' water consumption is further disaggregated into 43 sectors according to the sectoral waste water discharge which are collected from the provincial statistical yearbooks (National Statistical Bureau of China, 2008a). In this study, we consider only Crops sector consumes green water. Total water consumption for the Crops sector is calculated by multiplying the crops areas by the water requirements per hectare. Green water is calculated by subtracting blue water from total water consumption. The water requirements per hectare of different crops are collected from Zhu, Giordano, Cai, and Molden (2003a).

Results

Supply chain effects

Direct water coefficient and total water multiplier are useful indicators to assess the water efficiency for each economic sector in terms of per unit of sectoral output and final consumption. In this study the input–output tables include 48 sectors. However, regional water consumption is only substantially affected via a small number of major water consuming sectors. The direct water coefficients and total water multipliers of a number of key economic sectors are presented in Table 5. These economic sectors are selected either because of their high water intensity, or because of their importance for final demand in monetary terms.

Direct water coefficient refers to the direct water consumption to produce one monetary value of sectoral output, and it indicates the direct effects of production activities on its domestic water resources. From Table 6 we can see that Crops require the largest

Table 4
Crop productivity and irrigation rate in the YRB.

	Crop productivity ton/ha						Irrigation rate %
	Wheat	Maize	Soybean	Tubers	Oil crops	Cotton	
Upper	3.00	5.93	1.32	2.62	1.54	0.97	35
Middle	3.65	4.93	1.66	2.90	1.68	1.11	38
Lower	5.69	6.04	2.09	6.18	3.68	1.09	65

Source: China Provincial Statistical Yearbooks 2008.

Table 5
Water consumption versus water withdrawal (%).

	Agriculture	Livestock	Industry	Service
Upper	0.65	0.86	0.57	0.62
Middle	0.87	0.86	0.58	0.70
Lower	0.96	0.92	0.81	0.89

Note: Water consumption is water withdrawal minus the water return flows to the basin, which is considered as blue water. Data source: YRCC 2007.

direct water input per unit sectoral output in all four regions followed by Livestock, Electricity and steam production, Chemicals, Paper, printing and publishing, Textile and fibre and Manufacturing food and drinks. Table 6 also shows substantial regional differences of sectoral direct water coefficients among the four study regions. Most of the key sectors in the upper reach have larger direct water coefficients than the same sectors in the other regions. This indicates that water consumptions of the key economic sectors in the upper reach are generally higher for their production activities compared to the other regions, in order to produce one unit sectoral output. Particularly, the water intensity of the Crops sector in the upper reach is more than 30 percent higher than the water intensity in the other regions.

The production of crops accounted for more than 85 percent of the total direct water consumption in the YRB, thus it is very important to investigate why the direct water intensity of crops in the upper reach is much higher than the intensities in the other two reaches. In the three reaches of YRB, most of the agriculture areas are used for the production of wheat, maize, soybean, oil crops and cotton. From the regional statistical database and the irrigation water withdrawal and consumption data presented by YRCC, we found that two main factors cause the regional difference of direct water coefficients for cropping.

One is because of the differences of crop productivity for the crops in the studying regions. Table 4 shows that crops productivity for most crops in the middle and lower reaches are higher than in the upper reach, and in particular, the productivity of wheat in the middle and lower reach are about 22 percent and 89 percent higher than the productivity in the upper reach. Table 4 also shows that the regional differences in crop productivity are clearly depending on the agricultural irrigation rate (irrigation land as share of total cultivated land). The lower reach has the highest irrigation rate (65percent) followed by middle reach (38 percent) and upper reach (35 percent).

The other factor influencing direct water intensity of crops is the effective use of water. From Table 5 we can observe that the in the lower and middle reaches, 96 percent and 87 percent, respectively, of water withdrawal for crops production activities are not flowing back to the basin, while this rate is only 65 percent in the upper reach. It reflects that the water efficiencies of the irrigation systems in the lower and middle reaches are much higher than the efficiency in the upper reach. Table 5 shows the water consumption rates from water withdrawal for the livestock, industry and service sectors. It also clearly shows that the water consumption rates in the lower reach are much higher than the other two reaches, which partially explains why the direct water coefficients in the lower reach are generally smaller than other two reaches.

The direct water coefficient exclusively concentrates on the water intensity of local production activities from domestic water resource, ignoring the supply chain effects on water resources in other regions. Nevertheless, it is important to assess the water efficiency taking the whole intra-regional and inter-regional supply chain effects into account. From Table 6 we can observe that the total water multipliers for some of the economic sectors are substantially larger than their direct water coefficients. Particularly, total water requirements of many secondary and tertiary sectors need a huge amount of inputs from water-intensive primary sectors, such as Crops and Livestock, to produce their own products for the final consumers, whereas there are no big differences between direct water coefficients and total water multipliers for Crops because of their low water input from other water intensive sectors. After tracing the whole intra- and inter-regional supply chains effects, the Livestock, Grain mill products and Processed food, have very large water coefficients as well as Textile and fibres and Leather and fur.

Regional virtual water flows

Virtual water flows are measured by the embedded water in trade among different regions. Virtual water in trade can significantly influence the region's "water consumption responsibility". In this section, we use virtual water flows to assess how the water as an input for economic activities has been imported or exported virtually among four study regions and how the results can help solve regional water scarcity by redistribution of water resources from water-rich to water-poor regions. Table 7 shows the regional virtual water balance in the upper, middle and lower reaches and the rest of China. From Table 7, we can observe that the whole YRB is a net exporter of both green and blue virtual water. It means that the total virtual water exported from the YRB is larger than the total virtual water imported to the basin. By distinguishing blue and

Table 6
Direct and total water intensity for 15 key economic sectors (m^3/10,000 Yuan).

	Upper		Middle		Lower		RoC	
	Direct	Total	Direct	Total	Direct	Total	Direct	Total
Crops	3116.1	3453.3	2318.4	2533.6	1733.1	1892.5	2623.2	2925.5
Livestock	402.4	1190.5	149.1	760.0	208.6	708.5	146.5	1109.9
Grain mill products	15.4	1026.2	10.3	916.2	6.8	998.9	5.7	1814.2
Processed food	15.4	667.5	10.3	597.2	6.8	700.1	5.7	1011.9
Alcoholic beverages	15.4	547.4	10.3	462.6	6.8	431.1	5.7	582.9
Textile and fibre	20.0	607.0	13.4	650.7	8.8	795.4	7.7	672.6
Leather and fur	4.2	512.1	2.8	473.8	1.8	325.7	1.4	408.6
Wearing apparel and footwear	4.2	223.7	2.8	467.6	1.8	400.7	1.4	369.3
Paper, printing and publishing	33.7	526.8	22.6	351.2	14.9	224.3	10.9	177.4
Chemicals	40.8	138.5	27.3	172.3	18.0	131.3	6.2	126.3
Transport equipment	4.1	52.1	2.7	55.3	1.8	34.6	1.1	51.6
Electricity and steam production	41.8	50.4	28.0	74.9	18.4	57.1	15.8	47.6
Construction	7.2	64.1	4.8	66.7	3.2	55.3	2.3	64.4
Hotel and catering services	3.7	335.1	5.0	394.6	4.5	256.5	2.9	589.1
Health services	2.1	47.3	2.9	81.6	2.6	61.8	2.8	99.5

Note: RoC denotes Rest of China.

Table 7
Virtual water flows between the four studying regions (in million m^3).

			Receiving region					
			Upper	Middle	Lower	RoC	*Total outflow*	Net outflow
Shipping region	Upper	Green	2805	185	17	5215	*8222*	1595
		Blue	4847	322	25	6958	*12,152*	5196
	Middle	Green	218	8555	231	14,994	*23,998*	6400
		Blue	103	3775	87	5302	*9266*	−565
	Lower	Green	39	309	1654	628	*2631*	−225
		Blue	110	929	4522	1585	*7147*	2114
	RoC	Green	3565	8548	954	347,114	*360,182*	7770
		Blue	1895	4805	399	171,336	*178,435*	6746
	Total inflow		*13,582*	*27,429*	*7,889*	*553,133*	*602,032*	

Note: RoC denotes Rest of China; Net outflow is total regional outflow minus total regional inflow. The results are based on the four region MRIO framework without taking international trade into account.

green water, we found that upper and middle reaches are net green water exporter, while in terms of blue water upper and lower reaches are net exporters. From Table 7 we also can observe that the trade flows between the three reaches in the YRB are much smaller than their trade flows with the Rest of China. The upper reach exported around half of its domestic blue water consumption to the rest of China and the Middle reach exported 62 percent of domestic green water consumption to the rest of China. The lower reach had relatively small virtual water flows with the rest of China, and the total export of blue water to rest of China accounted for 22 percent of the total local blue water consumption.

Regional domestic and total water footprints

Domestic water footprint is the total water consumed by local production and consumption activities from its domestic water resources, which includes domestic water consumption for domestic final use and export. Therefore, it is a useful indicator for assessing the effects of regional production and consumption activities on local water resources. Table 8 shows that after tracing the supply chain effects, the share of water consumption for Crops is much smaller than usually claimed in the literature (e.g. Chapagain & Orr, 2008; Hoekstra & Chapagain, 2007, 2008). In the upper and middle reach, 66 percent of the domestic water consumption was used for producing goods and services for export, while only one third was for domestic final consumption. Significant contributors to the large exporting water footprints were exports of Processed food, Crops, Livestock and Wearing apparel and footwear products. In the middle reach, additional larger contributors were exporting Grain mill products, Alcohol and beverages, Construction and Hotel and catering services. In the lower reach, exports were responsible for 50 percent of the total domestic water footprint, and was mainly caused by exporting Crops and Processed food.

It is also interesting to look at the structure of domestic water footprints in terms of domestic final demand. In the upper and middle reaches, 38 percent and 44 percent of their domestic water consumption for domestic final demand were used for producing crops directly consumed by local households. It means that these two regions' households consume a large amount of crops directly without further processing for processed food products. In contrast, the share was only 13 percent in the more developed lower reach, which has, on the other hand, a relatively larger domestic water footprint for processed food.

The total water footprint can be used for identifying how much a region's consumption rely on domestic water resources and water resources from other regions. Fig. 3 provides an illustration of total water footprints for the regions in the YRB, distinguishing the amount of water consumed by local consumption activities from domestic water resources and water sources located in other regions. From Fig. 3 we can see that the middle reach has the largest total water footprint followed by upper and lower reaches, where

Table 8
Domestic water footprints of key economic sectors in the YRB (million m^3).

	Upper		Middle		Lower	
	Domestic FD	Export	Domestic FD	Export	Domestic FD	Export
Crops	3059	2579	5942	4628	923	1188
Livestock	845	1701	965	2414	347	398
Grain mill products	465	939	1015	1715	658	486
Processed food	648	2919	802	4178	2065	1310
Alcoholic beverages	270	657	417	1155	264	159
Textile and fibres	90	290	214	538	196	765
Leather and fur	20	373	109	565	50	115
Wearing apparel and footwear	34	1143	120	2003	167	315
Paper, printing and publishing	60	93	107	164	20	66
Chemicals	112	260	119	468	39	200
Transport equipment	14	203	72	375	38	70
Electricity and steam production	79	28	69	48	3	11
Construction	468	888	545	1681	240	387
Hotel and catering services	494	734	350	1137	171	201
Health services	67	240	51	431	50	65
Others	925	2494	1431	4362	946	1097
Household	361	–	1160	–	538	–
Total	*8012*	*15,542*	*13,490*	*25,862*	*6715*	*6832*

Note: FD denotes final demand. Export includes both domestic export and international export.

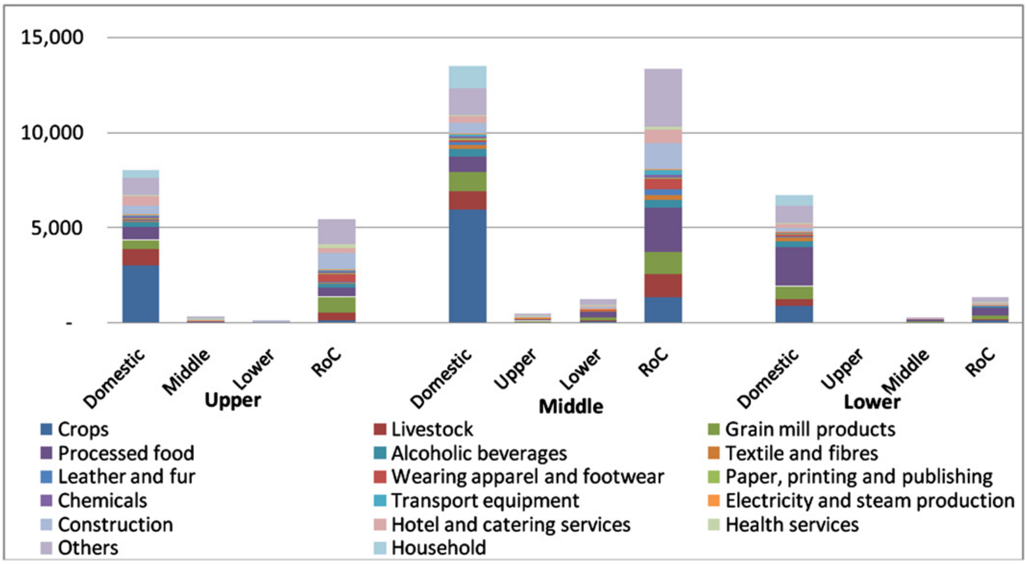

Fig. 3. Regional total water footprints of the YRB (million m^3). Note: Domestic refers to domestic water resources consumed by local production and consumption activities in each reach. The other bars refer to the contribution of other regions to the total water footprints.

about half of the total water footprints for the middle reach were from purchasing goods and services produced elsewhere in China. From Fig. 3 we can also see that the total water footprints of the upper and middle reaches are mainly fed from external water sources through importing secondary products rather than the usually dominating crops. This can be explained by the structure of the regional economies in the two reaches which are significantly relying on primary production and imports of secondary products. It is also interesting to point out that the lower reach as the most water scarce region in the basin has relatively small contribution to the total water footprint from imports, which implies that the lower reach mainly used its domestic water resources for local production and consumption activities. Thus, the reach has a large potential of increasing the virtual water import through importing water intensive goods and services from other water-rich regions in China.

Water footprints of urban and rural households

This section links water consumption to urban and rural household consumption patterns in the three reaches of the YRB. Fig. 4 shows that water footprints are closely related to income: urban households have larger footprints than rural ones and households in the lower reach have higher water footprints than households in the other areas. However, the gap between the three reaches becomes much smaller in terms of urban household water footprints than the rural household water footprints due to converging per capita urban household incomes between the three reaches.

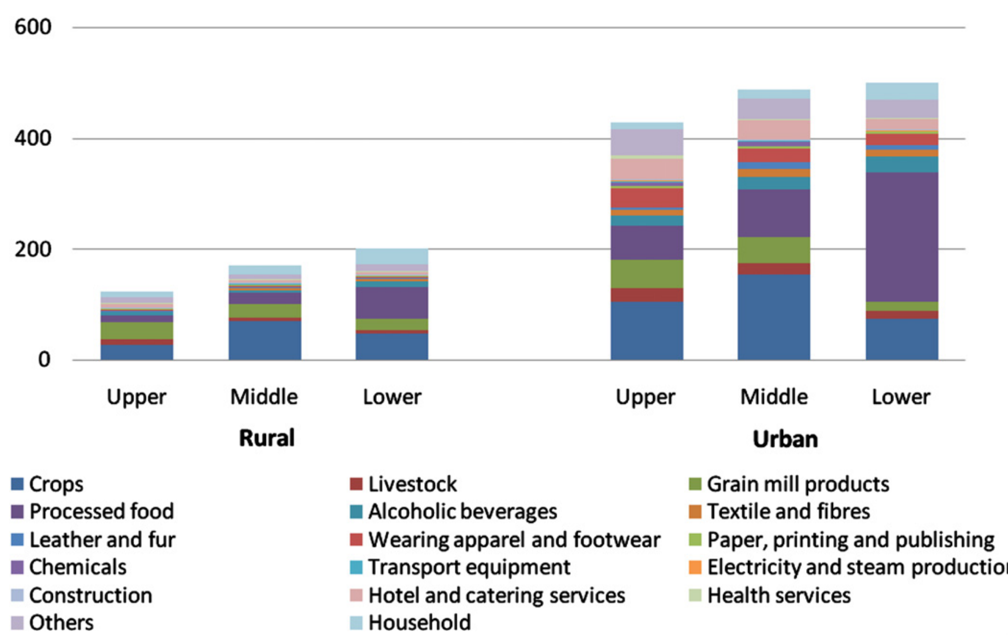

Fig. 4. Household total water footprints per person in the YRB and the Rest of China (m^3/cap/year).

Fig. 4 also shows that the water footprints for urban households (more than 400 m^3/person) were more than double of the water footprints for the rural household (less than 200 m^3/person) as urban households consumed more on most consumption items. In addition to Crops, Grain mill products, and Processed food, urban household also have huge consumption of Wearing apparel and footwear and Hotel and catering services. This is due to the much higher income levels of urban households, thus consuming more luxury items.

Discussion and conclusions

Given a water constraint economy, one can either increase supply (e.g. through water transfer), increase water productivity, decrease final demand or change the structure of production. The water multipliers calculated in this study show where inefficiencies occur in the economy and which sectors should be prioritized to achieve highest economic output per unit of water. Our analysis shows that there are large differences within the three reaches, in terms of direct water coefficients for Crops, which have strong supply chain effects on the water intensity of the overall economy. The large direct water coefficient of Crops in the upper reach is strongly driven by the huge amount of blue water inputs for irrigation. This is partly due to the inefficiency of the largely traditional irrigation systems, which also leads to lower land productivity. The land productivities in the upper and middle reaches are much lower than in the lower reach for the same types of crops. Thus, investment in more efficient irrigation in the upper and middle reaches would reduce water pressure and at the same time increase land productivity.

Virtual water flows can provide an option for solving the regional water scarcity. For example, in the case of YRB, the lower reach is a net virtual water exporter for blue water. As serious water scarce area, the lower reach exports about 37 percent of its blue water to other areas through inter-regional trade, in particular crops and processed food products. The lower reach could substantially benefit from reducing the export of water intensive and low value added products and using the blue water for the production of higher value added products, in the meantime, importing these high water intensive and low value added products from water-rich regions, particularly from the water abundant South of China. The upper reach is a comparatively water-rich region which is also reflected in its water balance showing exports of large amounts of virtual water by exporting agricultural and food related products to other regions.

Another frequently overlooked but important factor is to influence final consumers and inform them about and make them responsible for the water implications of their consumption choices. Water footprints allow us to identify sensitive consumption categories; and policy tools such as labels, education and prices for life cycle water consumption can help inform and incentivise consumers. Water footprint analysis is an important precondition to provide the necessary information of water implications. Putting a price on water or labelling water intensive products can help improving sectoral water efficiency as well as directing householders' choices towards lower water intensive goods and services. In addition, pricing water in water scarce regions, such as the lower reach, can stimulate the import of water intensive goods and reduce the stress on domestic water resources. This might have important structural and social implications and thus needs to be carefully evaluated. Water is a significant factor for regional sustainable development and should be taken into account along with other environmental and social factors, such as land accessibility and local infrastructure in regional and national policy making.

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