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Lifting China's Water Spell

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ABSTRACT

China is a country with significant but unevenly distributed water resources. The water stressed north stays in contrast to the water abundant and polluted south defines China's current water environment. In this paper we use the latest datasets and adopt structural decomposition analysis for the years 1992 to 2007 to investigate the driving forces behind the emerging water crisis in China. We employ four water indicators in China, i.e. freshwater consumption, discharge of COD (Chemical Oxygen Demand) in effluent water, cumulative COD and dilution water requirements for cumulative pollution, to investigate the driving forces behind the emerging crisis. The paper finds water intensity improvements can effectively offset annual freshwater consumption and COD discharge driven by per capita GDP growth, but that it had failed to eliminate cumulative pollution in water bodies. Between 1992 and 2007, 225 million tonnes of COD accumulated in Chinese water bodies, which requires 3.2 ~ 8.5 trillion m^3 freshwater, depending on qualities of water resources, to dilute those pollution to a minimum re-usable standard. Cumulative water pollution is a key driver to pollution induced water scarcity across China. In addition, urban household consumption, export of goods and services, and infrastructure investment are the main factors contributing to accumulated water pollution since 2000.

TOC ART


rust metal pipes discharge wastewater to a local stream, North China
9000 billion m³
6000 billion m³
3000 billion m³
Exports
Capital formation
Government
Urban households
Rural households
1992
1995
1998
2001
2004
2007
Dilution water requirement for cumulative COD by final demand consumption

1 Introduction

The continuous rapid and large-scale economic development and recent double-digit economic growth largely driven by construction and export production have resulted in China becoming the second largest global economy and the world's largest exporter. These remarkable achievements have been at a tremendous environmental cost, particularly to the aquatic environment. China has abundant freshwater resources in terms of total availability, ranked as the world's 6th largest, however per capita volume is almost 2,000 m^3 p.a. which amounts to one-fourth of the global average[1]. China's water resources are unevenly distributed: northern China has only about 20% of the total water resources in China, but is supporting more than half the total population. Furthermore, widespread pollution has resulted in 75% of lakes and rivers and 50% of groundwater supplies becoming contaminated[2]. This situation has caused concern for the water abundant regions of China (e.g. South China) for the lack of available water even for agricultural use. To combat this, the Chinese Government has introduced a series of legislative instruments to conserve water resources and has invested substantially in constructing wastewater treatment plants servicing almost all large cities[3]. However, the level of aquatic pollution has not improved but has, in fact, worsened. For example, China's annual available surface water resources for non-industrial or irrigation purpose has declined from 65% of total annual availability in the early 1990s to around 60% by 2007[4].

In order to address its projected cumulative economic growth of 60% by 2020[5], China announced an ambitious plan to cut "*water consumption per 10,000 Yuan of GDP to 125* m^3 *by 2020, down 60% from now*"[6]. Furthermore in 2011, China announced that it will invest four trillion Yuan (~US$600 billion) over the next ten years in infrastructure development, about one-third of which will be used to improve and protect access to freshwater[7]. Moreover, China begins the most stringent water management system in 2014 to strengthen water environment conservation. The message from the Chinese Government suggests that (a) the Government is determined to tackle water availability and quality to sustain socioeconomic development; (b) China is confident with, and will rely on, constructing more water related infrastructure using the latest technologies in an attempt to offset future increasing demand for water resources and resulting pollution; (c) economic production may largely follow the same pattern as previously. These points serve to illustrate some influencing factors in

China's emerging water crisis, for example technology, production and consumption patterns and water policy and management.

This paper aims at identifying and understanding the major socio-economic driving forces behind China's emerging water crisis by taking both water consumption and pollution into consideration. The study will firstly establish hydro-economic accounting inventories[8] for China for the years 1992 – 2007. The account for each year will produce four water indicators (see definitions in Supporting Information) – water consumption, discharged COD in effluent water, cumulative COD discharge and dilution water requirements for cumulative pollution. Secondly, we conduct full structural decomposition analysis (SDA) to illustrate the contribution of each driving force to water consumption and cumulative degradation in China over the study period. The decomposed driving forces consist of population, water consumption intensity, economic production structure, final demand pattern and per capita final demand volume. We attribute the growth of water stress in China to household consumption, governmental consumption, capital formation, and export production from a consumption accounting approach. Finally, the paper discusses the limitations in China's water resource policies and closes with some recommendations to help China step back from its emerging water crisis.

2 Selective review of water input-output analysis in China

In recent decades input-output modelling has been popularly applied to water research in China. A water input-output model allows one to quantify the water consumption or pollution throughout the whole life-cycle of a product. For example, Guan and Hubacek[9] developed a regional water input-output model to estimate virtual water flows for water abundant South China and water scarce North China. Some extended studies were conducted by using input-output analysis to quantify China's water footprint at both national[10, 11] and regional levels[12, 13]. Overall China is a net virtual water exporter. Similar work has been conducted at regional and watershed level[14]. Hubacek and Sun[15] adopted input-output modelling techniques to conduct scenario analysis forecasting water consumption for China's economy in 2025. Ni et al.[16] conducted a regional study on one of the fast-growing economic zones, Shenzhen in South China. They added a pollution factor into the input-output tables, aimed at adjusting the economic structure for minimising the COD level in industrial wastewater discharges by giving a predicted maximised GDP. Okadera et al.[17] accounted for water demand and pollution discharge (carbon, nitrogen and phosphorus) based on input-output analysis for the city of Chongqing. Guan and Hubacek[8] developed an integrated hydro-economic accounting framework to quantify the total impact of wastewater to North China's water bodies.

In recent years, Chinese water consumption has been studied in the context of virtual water flows and water footprinting at regional level. For example, Feng et al.[18] designed an interregional input-output model for the Yellow River Basin to calculate the water footprints for upper, middle and downstream sections of the Yellow River Basin as well as virtual water trade among those regions. Zhang et al. [19] developed an interregional input-output table to measure Beijing's water footprints for 30 provinces. Lin et al.[20] used a hybrid input-output analysis with life cycle analysis to study the water consumption cost and benefit of China's North-South water transfer project. There are also a few empirical studies to assess the driving forces of China's water consumption or pollution using structural decomposition analysis (SDA). For example, Zhang et al.[21] adopted SDA to measure the magnitude of socioeconomic driving forces in Beijing's water consumption changes over 1997 – 2007. However, studies investigating the driving forces of China's water consumption or pollution at national scale have not been conducted. Furthermore, previous water research has focused on assessment of the implication of annual water consumption and pollutants[22]. The present study is a pioneer in quantifying socioeconomic contributions to cumulative water pollution and impact to China's water environment. This would help identify the hidden drivers in China's water crisis and provides the foundations for its national policies on sustainable water management.

3 Methods and Data

3.1 Hydro-economic inventories

In this study we created seven Chinese national hydro-economic annual inventories for the years 1992, 1995, 1997, 2000, 2002, 2005 and 2007. The accounting method of the constructed inventories is based on extended economic-ecological input-output analysis[23-26]. The following sections utilize some mathematical symbols, formulas and equations. Here, for clarity, matrices are indicated by bold upright capital letters (e.g. $\mathbf{X}$); vectors by bold upright lower case letters (e.g. $\mathbf{x}$); and scalars by italicised lower case letters (e.g. x). Vectors are columns by definition, so that row vectors are obtained by transposition, indicated by a prime (e.g. $\mathbf{x}'$). A diagonal matrix with the elements of vector **x** on its main diagonal and all other entries equal to zero are indicated by a circumflex (e.g. $\hat{\mathbf{x}}$).

Each inventory contains four inter-linked matrices that describe the interrelationship between economic activities and hydrological processes[8]. In particular, Matrix **F** ($m \times n$) represents the primary water inflows (e.g. from surface, ground (i.e. aquifer) or rainfall) to the economic system for production purposes; Matrix **A** ($m \times n$) represents economic production structures and technologies; Matrix **R** ($n \times m$) represents environmental emissions (COD effluence) i.e. outflows to natural aquatic systems after economic production and consumption; and Matrix **B** ($m \times m$) quantifies the impact of discharged COD on hydrological systems (e.g. dilution water required for COD discharge). The structure of the hydro-economic accounting model is shown in Table 1. The calculation of contaminated water is the amount of freshwater necessary to dilute COD discharged to a respective standard pollution concentration level (that is, for example, stated in the regulations of water quality and management). A similar approach of using dilution in calculating pollution impact has been adopted in 'grey water' accounting water footprint studies[27-29].

<table>
<tr><th colspan="2" rowspan="2">Units in "( )"</th><th rowspan="2">Activities Intermediate Demand</th><th colspan="2">Final Demand</th><th rowspan="2">Total Output</th><th colspan="3">**Hydrological system**</th></tr>
<tr><th>Household & Governments</th><th>Exports</th><th>Surface water</th><th>Ground water</th><th>Natural losses</th></tr>
<tr><td colspan="2">Economic Activities</td><td>x_{ij} (Yuan)</td><td>y_{ij} (Yuan)</td><td>w_{ij} (Yuan)</td><td>x_i(Yuan)</td><td colspan="3">h_{il} (m^3)</td></tr>
<tr><td colspan="2">Primary Inputs</td><td rowspan="2">Matrix **A**</td><td colspan="2" rowspan="2"></td><td></td><td colspan="3" rowspan="2">Matrix **R**</td></tr>
<tr><td colspan="2">Imports</td><td></td></tr>
<tr><td colspan="2">Total Inputs</td><td>x_j (Yuan)</td><td colspan="2"></td><td></td><td colspan="3">h_l (m^3)</td></tr>
<tr><td rowspan="3">**Water inputs**</td><td>Surface water</td><td rowspan="3">g_{kj} (m^3)
Matrix **F**</td><td colspan="2" rowspan="3"></td><td rowspan="3">g_k (m^3)</td><td colspan="3" rowspan="3">d_{kl} (m^3)
Matrix **B**</td></tr>
<tr><td>Ground water</td></tr>
<tr><td>Rainfall</td></tr>
</table>

Table 1: Hydro-economic accounting framework (modified after Guan and Hubacek[8]).

The four matrices capture annual exchanges between the economic and hydrological systems. Pollutants entering the hydrological system would be completely mixed and distributed in the water bodies in a dynamic process contaminating other freshwater resources thus rendering them unavailable for other uses and subsequent round(s) of economic production and consumption. The hydro-ecosystem may have the ability to assimilate some of the pollution, but this ability is determined by local hydrologic conditions and the biological, physical and chemical characteristics of the pollutants. For example pollutants discharged from heavy polluting industries (e.g. paper making) may contain large amounts of environmentally toxic chemicals which are not assimilated by nature in any economically relevant time frame. In other words, those bodies of water would require additional freshwater to dilute their pollution concentrations to a required standard level. In this paper we account for cumulative COD discharges in China's hydro-ecosystem between 1992 and 2007, and the total water resources required to dilute those pollutants to meet prevailing regulatory standards (for further methodological details, see Supporting Information, section 1.2).

3.2 Structural decomposition analysis

SDA is an "*analysis of economic change by means of a set of comparative static changes in key parameters in an input-output table*[30]." SDA has been applied to analyse people's demand, technology improvements and other driving forces which contribute to the environmental changes. An important feature of SDA is its capability to distinguish the direct and indirect components of the observed sectoral changes or driving forces (e.g. changes in final demand, productivity changes and so on)[31]. SDA is a particularly powerful method to account for the indirect effects on one production sector of structural and productivity changes that take place in the other production sectors and are transmitted through the intermediate transactions. SDA studies focussing on energy and related emissions have been performed for China [32-41].

The principal formula for *water SDA* can be illustrated as **Water Consumption** $= p \cdot \mathbf{F} \cdot \mathbf{L} \cdot \mathbf{y}_\mathbf{s} \cdot y_v$. Water consumption can be decomposed into five driving forces: population (p), water consumption intensity ($\mathbf{F}$) i.e. the amount of freshwater consumed to produce a unit of industrial output, economic production structure ($\mathbf{L}$), final demand pattern ($\mathbf{y}_\mathbf{s}$) and per capita final demand (y_v). The change in freshwater consumption from time *t-1* to time *t* can be decomposed into changes in the component driving forces, but there is no unique solution for the decomposition; the five factors utilized in this paper have *5!=120* first-order decompositions[42]. One of the 120 possible decompositions is shown in Equation 1.

$$
\begin{aligned}
\Delta \mathrm{Water} &= \Delta \mathrm{Water}_{(\mathrm{t})} - \Delta \mathrm{Water}_{(\mathrm{t}-1)} \\
&= p_{(\mathrm{t})} \cdot \mathbf{F}_{(\mathrm{t})} \cdot \mathbf{L}_{(\mathrm{t})} \cdot \mathbf{y}_{\mathbf{s}(\mathrm{t})} \cdot \mathbf{y}_{\mathbf{v}(\mathrm{t})} - p_{(\mathrm{t}-1)} \cdot \mathbf{F}_{(\mathrm{t}-1)} \cdot \mathbf{L}_{(\mathrm{t}-1)} \cdot \mathbf{y}_{\mathbf{s}(\mathrm{t}-1)} \cdot y_{v(\mathrm{t}-1)} \\
&= \Delta p \cdot \mathbf{F}_{(\mathrm{t})} \cdot \mathbf{L}_{(\mathrm{t})} \cdot \mathbf{y}_{\mathbf{s}(\mathrm{t})} \cdot y_{v(\mathrm{t})} + p_{(\mathrm{t}-1)} \cdot \Delta \mathbf{F} \cdot \mathbf{L}_{(\mathrm{t})} \cdot \mathbf{y}_{\mathbf{s}(\mathrm{t})} \cdot y_{v(\mathrm{t})} \\
&+ p_{(\mathrm{t}-1)} \cdot \mathbf{F}_{(\mathrm{t}-1)} \cdot \Delta \mathbf{L} \cdot \mathbf{y}_{\mathbf{s}(\mathrm{t})} \cdot y_{v(\mathrm{t})} + p_{(\mathrm{t}-1)} \cdot \mathbf{F}_{(\mathrm{t}-1)} \cdot \mathbf{L}_{(\mathrm{t}-1)} \cdot \Delta \mathbf{y}_\mathbf{s} \cdot y_{v(\mathrm{t})} \\
&+ p_{(\mathrm{t}-1)} \cdot \mathbf{F}_{(\mathrm{t}-1)} \cdot \mathbf{L}_{(\mathrm{t}-1)} \cdot \mathbf{y}_{\mathbf{s}(\mathrm{t}-1)} \cdot \Delta y_v
\end{aligned}
\qquad (1)
$$

Each of the five terms in Equation (1) represents the contribution to change in water consumption triggered by one driving force whilst keeping the rest of the variables constant. For example, the first term — $\Delta p \cdot \mathbf{F}_{(t)} \cdot \mathbf{L}_{(t)} \cdot \mathbf{y}_{s(t)} \cdot y_{v(t)}$ represents the change in water consumption due to changes in population, with all other variables (**F**, **L**, $\mathbf{y}_s$ and y_v) remaining constant. This also serves to highlight a methodological issue with SDA – non-uniqueness. For instance, in the fourth term **F**, **L**, $\mathbf{y}_s$ and y_v can be evaluated at the start or the end-point of the time-period investigated. There are several methods for dealing with this issue. Here we average all possible first-order decompositions; for a detailed discussion see Hoekstra & van der Bergh[31]. Please also refer to the SI for matters about uniqueness and weighing in SDA.

3.3 Removing imports columns from water I-O model

The standard environmental input-output model assumes that imports are produced with Chinese technology. This is clearly inadequate given the differences in production and water consumption and emissions across countries. There are several world multi-regional input-output (MRIO) models with environmental datasets available (e.g. EXIOPOL, EORA and WIOD), but the water related data shows significant variance within/between environmental MRIO databases and the official Chinese statistics that are used in this study. EXIOPOL[43] collected national water usage and pollution datasets for the year 2000 for 8 sectors, which were then disaggregated into 129 sectors to match the economic sectors. WIOD [44] conducted water footprint accounting[45] to calculate water consumption (green and blue water) and pollution (grey water) for all countries using data for 35 sectors from 1995 – 2009. Official Chinese statistics are largely inconsistent with these water footprint databases. These prevent us from integrating our national water input-output model with the global MRIO models to quantify the embodied water and emissions in Chinese imports. Therefore we have removed imports from the input-output data to give a clearer picture of the role of domestic components as the driving force in China's emissions growth. It is common to derive new requirements matrices (**A**) and final demand vectors (**y**) in which only domestic goods are included, $\mathbf{A_d}$ and $\mathbf{y_d}$. The core assumption of this method is that every economic sector and final demand category uses imports in the same proportions since there is no import matrix available for China but only a column of imports. Further explanation to this approach can be found in our previous work [37, 46, 47]. After removing the import column, we are able to only calculate the embodied water or COD emissions within Chinese domestic production supply chains. The environmental impacts from Chinese imports are excluded from our analysis.

3.4 Data

This study requires two sets of data: time-series input-output tables and the corresponding sectoral water consumption and COD discharges.

We consistently aggregated seven national input-output tables from 1992 to 2007 for 31 sectors at 2002 producer prices using the double deflation method [48] (see Supporting Information). The price deflation data was obtained from the Chinese Statistical Yearbook[49]. The Chinese input-output tables are published by Chinese National Statistics Bureau, and include several categories of final consumption: rural and urban households, government, total capital formation, and exports.

We compiled a time-series water inventory for the study period that consists of the physical volumes of freshwater consumed and COD discharged. In this paper we use COD as an overall water pollutant indicator measured in $grams/m^3$. The water pollutants dataset also consists of other indicators such as heavy metals (mercury, lead, and arsenic), cyanide, and ammoniacal nitrogen etc., which are not utilised in this study.

- Data sources for freshwater consumption: *China's Annual National Water Bulletins*[4] provided total consumption for surface and ground water and its sectoral detail in agriculture, industry and for domestic consumption. Water consumption data in sectoral detail were reliant on Chinese official water consumption census data from 2008, which provided water consumption in 40+ economic sectors[49], and 1997 and 2002 data provided from other literature[9, 50]. Since the Chinese official statistics do not provide water consumption data for detailed economic sectors every year, a series of normalization procedures were made in this study (for details, see Supporting Information – section 2.3). Chinese official statistics do not distinguish water consumption between household and service sectors. We calculated the household water consumption by using daily household consumption data from the *China Urban Water Supply Bulletin*. The water consumption for service sectors is the difference of the total residential consumption and household consumption (see Supporting Information - section 2.3).
- Data sources for the amount of COD discharged: *China's Environmental Statistics Yearbook* [51] provided annual COD discharges (measured in *tonnes*). The water census[49] verified and updated national and regional COD discharge data. COD discharge for

agriculture and service sectors are not available in Chinese official statistics. We utilized fertilizer consumption as a proxy to estimate the COD discharge in the agriculture sector. The same techniques were used in our previous paper[8]. Chinese official statistics provided total residential COD discharge without the distinction between household and service sectors. We utilized the water consumption proportion in residential water consumption between household and service sectors as a proxy to estimate the COD discharge in service sectors (see further description at Supporting Information - section 2.4). Data descriptions for a mass-balanced hydrology model (see Supporting Information Equation 8) employed to estimate dilution water requirements is available in Supporting Information, Section 2.4.

4 Results

4.1 Efficiency gains reduce annual water consumption and pollution

In the 15 years between 1992 to 2007 China's GDP has grown fourfold whilst it's gross freshwater consumption and COD discharges decreased by 7% (from 285 to 266 billion tonnes) and 19% (from 21 to 17 million tonnes), respectively. Efficiency gains (measured by water intensity reduction – i.e. freshwater consumption / industrial outputs at sectoral level) has played a key role in reducing annual freshwater consumption and pollution discharges. Our structural decomposition analysis shown that if China's population, economic structure, and per capita GDP (final demand volume) had remained constant, efficiency gains would have saved 417 billion tonnes (decreased by a factor of 1.5) freshwater consumption (shown in Figure 1a), and diminished by 55 million tonnes (decreased by a factor of 2.6) COD discharged (shown in Figure 1b) from 1992 level. China's technology improvements for water consumption and COD discharges are strongly related to policy interventions. For example, the rapid decrease of COD discharge after 1997 is mainly attributed to the "Closure of the 15 types of small enterprises (so called 'The 15 Smalls') with inefficient technologies" implemented in 1998[52]. In addition, China's population is changing its gross consumption patterns towards consumption items with lower water intensity (e.g. quickly increasing proportions of services related consumption)[21]. The improved consumption patterns would have reduced freshwater consumption by 247 billion tonnes (-86%) and 7 million tonnes (-36%) COD discharges.

In contrast, without China's water intensity and consumption pattern improvements the increased per capita GDP would have led to an increase of 576 billion tonnes (202%) freshwater consumption and 47 million tonnes (224%) COD emissions. Population growth or production structure changes would have led to 46 (16%) or 23 billion tonnes (8%) increase in freshwater consumption and 4 (18%) or 8 million tonnes (40%) in COD discharges.

We have only analysed water consumption and resulting pollution from the production of products and services which represents about 85% – 90% of China's total water consumption and COD discharge during the study years. The remaining 10%-15% are from direct household consumption, i.e. arising from activities such as drinking, cooking and washing in the home. Direct domestic water consumption has increased from 26,603 million tonnes in 1992 to 36,704 million tonnes in 2005, and further to 37,473 million tonnes by 2007.

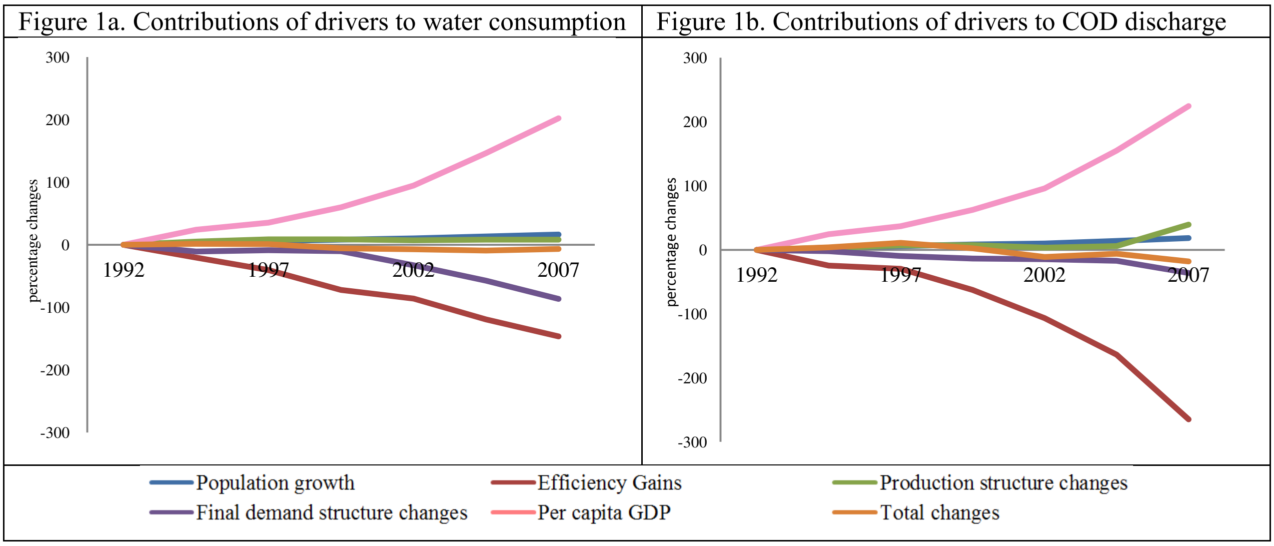
Figure 1a. Contributions of drivers to water consumption

Figure 1b. Contributions of drivers to COD discharge

Figure 1. The orange line shows the percentage change ('*y*' axis) in water indicators – 1a for water consumption and 1b for COD discharges). Other coloured lines represent the contribution to change from population growth (blue), efficiency gains (red), structural changes (green), consumption pattern changes (purple), and per capita GDP growth (pink).

4.2 Manufacturing is the largest water user from a consumption perspective

Agriculture is the largest *direct* water consumer in China, which accounts for over 60% of China's annual water consumption[53]. Direct water consumption intensity in the agricultural sector (defined as the amount of water consumed per 10,000 Yuan (USD\$1600) of agricultural output) has improved more than six fold from 217 m^3 in 1992 to 34 m^3 in 2007, although it remains at twice the current US level and one-fifth of the Indian figure[45]. Irrigation efficiency and pipeline leakage have been significantly improved over the past two decades. On the other hand, if we take *indirect* water consumption (amount of water embedded in products throughout the whole production supply chain) into consideration, agriculture accounted for 55% (158 billion m^3) of production-related water consumption in 1992 from a consumption based accounting approach. Further, this figure drops to 31% (82 billion m^3) by 2007, which places agriculture as the second largest water consumer after manufacturing (47%) in 2007, but ahead of the service (13%) and construction (8%) sectors.

Manufacturing also dominates contributions to water pollution. Total manufacturing sector annual COD discharges have been reduced from 13.7 million tonnes to 9.5 million tonnes over the study period. From a direct COD discharge perspective, paper production and food & tobacco processing accounted for 25% (5.2 million tonnes) and 16% (3.3 million tonnes) of total annual COD discharges in 1992, respectively. These figures are reduced to 19% (3.3 million tonnes) and 11% (1.9 million tonnes) of total COD discharged by 2007, respectively. If we investigate COD discharges from a consumption based perspective, paper production and food & tobacco processing sectors accounted for 16% (3.3 million tonnes) and 12% (2.6 million tonnes) of COD discharges in 1992; and these figures declined to respectively 12% (2.1 million tonnes) and 5% (0.8 million tonnes) by 2007.

4.3 Cumulative pollution pushes China towards water crisis

China's water resources are increasingly unable to cope with demand even though water consumption has decreased slightly (i.e. by 7% over the 1992-2007 study period). Instead it has largely been driven by the rapid increase in so called 'cumulative pollution'. China classifies its water resources according to five quality categories; the bottom two levels (IV to V) are for water polluted to varying degrees but which remain usable for certain economic purposes[54]. In addition, China added the 'V+' category to grade the most seriously polluted water which is unavailable to serve for any economic purpose [8]. During 1992 – 2007, China discharged between 17 – 21 million tonnes of COD per year to its surface and groundwater bodies [51]; the total COD discharged was 317 million tonnes. The hydro-ecosystem has some capacity to assimilate this pollution (including biological and natural chemical and physical processes and drainage to sea), but such assimilation is in decline as cumulative emission levels increase. Between 1992 and 2007, we estimate the hydro-ecosystem was able to assimilate 92 million tonnes of COD due to natural self-purification. Therefore, cumulative COD is estimated to be 225 million tonnes over the study period. Further, the cumulative pollution is unevenly distributed (see Supporting Information Figure 2&3). Those economically advanced coastal provinces produced two-third of annual GDP and accounted for 43% of cumulative pollution over the study period. In 2007, water categorised as V+ in the most water abundant Chinese coastal regions such as Jiangsu and Shanghai accounted for over half the volumetric water resources[4]. The direct implication of those cumulative pollution is to cause water scarcity in water abundant regions for the lack of eligible water to consume, so-called pollution induced water scarcity[28]. The average per capita water availability in coastal China is over 2,000 m^3, but the amount that is within the regulatory standard is only about 40% of the total or 800 m^3 per capita. In general regions with water availability of less than 1,000 m^3 per capita are considered as water scarce[55].

The cumulative COD effluence has worsened China's overall water quality. In particular, it has caused that the proportion of grade V+ surface water increased from 12% to 22% of annually available water over the 1992 – 2007 study period[4]. Dilution water requirements for pollution has been used as a quantification indicator to measure potential hydro-ecosystem impact by pollution discharge[8, 28, 29]. China would require approximately 4.2 trillion m^3 of grade II or better freshwater (with COD level $\leq$ 15 gram/m^3) or 8.4 trillion m^3 of grade IV water (COD level = 30 gram/m^3) in order to dilute the 225 million tonnes of cumulative COD to the minimum regulatory level (e.g. grade V for irrigation purposes only). These hypothetical figures are 1.7 – 3.4 times larger than China's annual water availability (e.g. ~ 2.5 trillion m^3 per year). But in reality, pollutants are constantly discharged to the same water bodies. Estimations for dilution water requirements vary across Chinese provinces (see Supporting Information section 3.2 for detailed discussion). The results for dilution water requirements illustrates the severity of pollution induced water scarcity in China. Reduce cumulative pollution and minimise dilution water requirements are the keys to mitigate water crisis in China.

4.4 Water crisis by final demand categories

The final demand perspective illustrates the environmental impacts of economic activities throughout whole supply chains [38, 40, 56, 57]. Figure 2 shows freshwater resource and pollution allocations for China as separate final demand categories and industrial sectors. As shown in Figure 2a rural household consumption was responsible for 115 billion m^3 (40% of total water consumption) in 1992, but the share has fallen to 52 billion m^3 (19%) by 2007. At the same time urban household consumption has increased from 28% (80 billion m^3) to 38% (101 billion m^3). This change is explained by the mass migration of some 122 million people into cities and their adoption of urban lifestyles as a result of large scale urbanisation.

Water consumption in capital investment and export production has increased rapidly from 19 billion m^3 to 40 billion m^3, and 43 billion m^3 to 51 billion m^3 per annum respectively, over the study period. On the other hand water intensity for all final demand categories (e.g. m^3 of water required per 10,000 Yuan or USD$1607 consumption) have declined, as shown in Figure 2b. Water intensity in the production of goods for export has declined rapidly (by 84%) due to changing exporting patterns and technology interventions in improving agricultural and manufacturing processes. Similarly both rural and urban household consumption intensities have declined by over 70%, and intensity for capital investment has declined by 68% due to efficiency gains in producing construction and machinery related materials and their supply chains.

Figure 2a. Annual water consumption by final demand

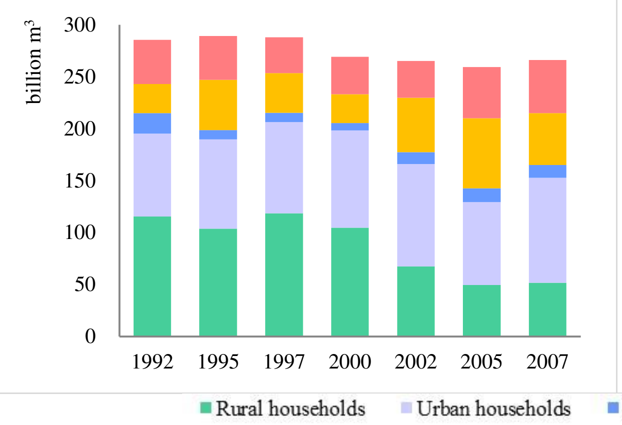

Figure 2b. Water intensities for final demand sectors

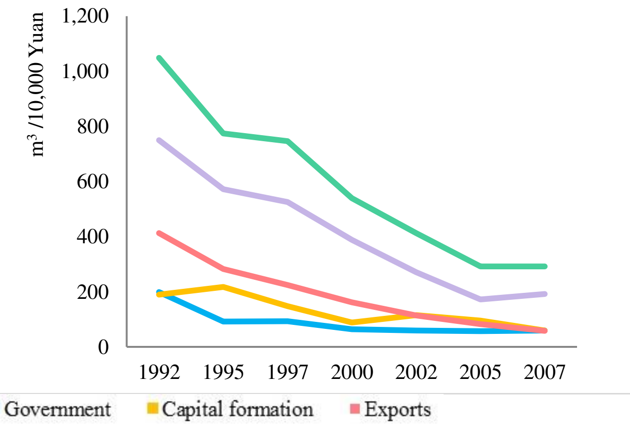

Figure 2c. Annual COD discharge by final demand

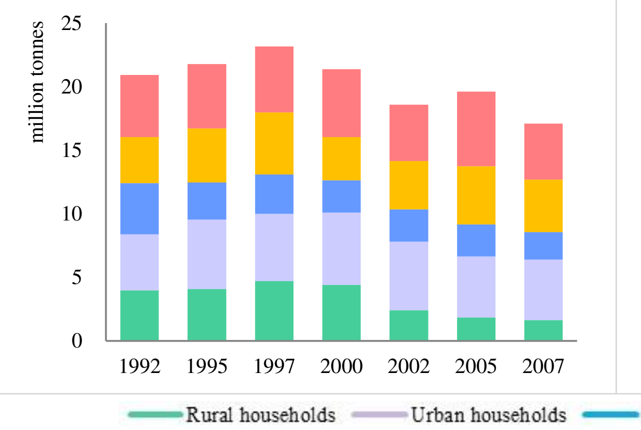

Figure 2d.COD intensities for final demand sectors

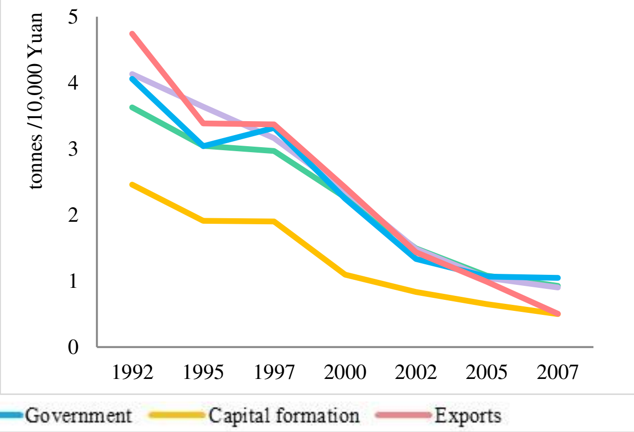

Figure 2e. Cumulative COD level over years by sectoral breakdown

Figure 2f. Dilution water requirements for cumulative COD by final demand breakdown

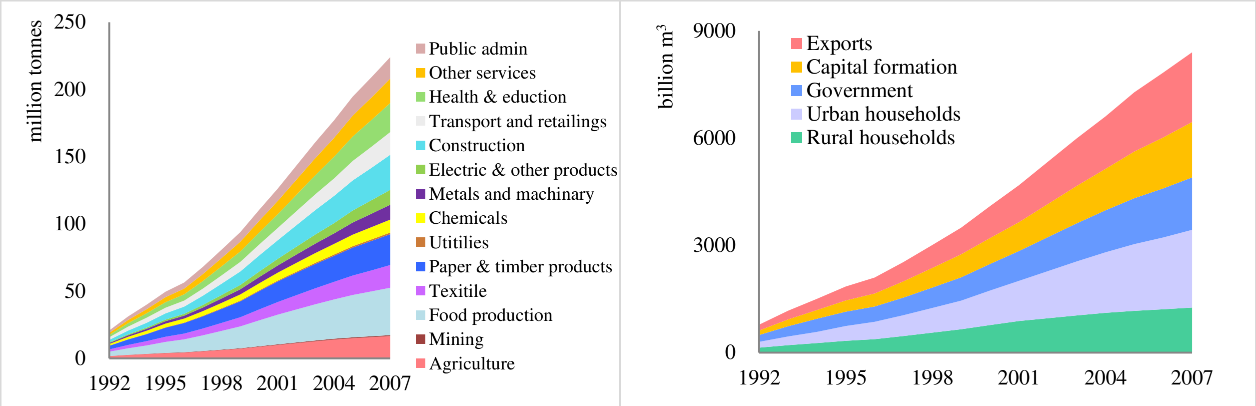

Figure 2. A changing assessment of China's water crisis from a consumption accounting perspective. Figures 2a and 2c illustrate final demand category contributions to annual water consumption and COD discharges. Figures 2b and 2d shows how annual water consumption and COD intensities change for different final demands. Figure 2e demonstrates industrial sectoral contributions to the cumulative pollution load increases between 1992 and 2007. Figure 2f decomposes water resources required to dilute cumulative pollution to standard regulatory levels by final demand categories.

Figure 2c describes an overall increase in annual COD discharges in China between 1992 and 1997, followed by an overall annual decrease until 2007. The allocation trend of pollutants between final demand categories is similar to water consumption; rural household consumption has experienced a 60% decrease in COD discharge, which is partially replaced by capital investment with a 14% increase, and urban household consumption (8%). In 2007, urban household consumption accounted for 28% of annual COD discharge, followed by exports (26%), capital investment (24%), government consumption (13%), and rural household consumption (10%). The COD intensities (tonnes per 10,000 Yuan or USD$1607 consumption) of all final demand categories have also declined by between 70% – 90% over the study period (shown in Figure 2d).

Figure 2e shows water pollutant COD accumulation in water bodies between 1992 and 2007 from an industrial sectoral consumption approach. Manufacturing is the largest contributor to cumulative COD levels. In particular, food processing, paper production and textiles accounted for 16%, 10% and 8% of total cumulative COD over the study period. Further, a shift to a service-based economy will not prevent an environmental crisis[58]. In fact, services are the second major contributor to cumulative COD in China, which contributes one-third of the total. For example, the health & education sectors contribute COD accumulations from 1 million tonnes in 1992 to 22 million tonnes in 2007, which accounts for 10% of total cumulative COD. The health sector requires pollution intensive production supply chains, i.e. medical machinery and production of pharmaceuticals. Similarly transportation & retailing and public administration contribute 8% (18 million tonnes) and 7% (16 million tonnes) of total cumulative COD over 1992 – 2007, respectively. Public administration includes general governmental activities (e.g. daily operations of local and national governing bodies and public policy design and implementations) and investments to national defence industries that had pollution intensive supply chains including heavy metal and machinery production. In addition, the construction sector is responsible for 12% of the cumulative COD due to rapid urbanisation and large-scale infrastructure investment since 2000.

Figure 2f takes a further step to quantifying each final demand category's contribution to the amount of freshwater required for remediating the pollution level to the least acceptable re-use standard (e.g. irrigation), grade V of the Chinese water quality standard. For example, if we estimate dilution water requirements by using grade IV water resources, the cumulative COD discharge due to urban household consumption nationally required 2.2 trillion m^3 freshwater resources in 2007 (to be diluted to the quality standard required for irrigation re-use), which accounts for 26% of the total. Similarly, 1.3 trillion m^3 of freshwater would be required to leverage cumulative COD from rural household consumption. In order to satisfy export requirements 2.0 trillion m^3 water resources would be required to dilute water pollution accumulated over the 1992 – 2007 study period, which in itself is almost the total annual available water resource for China. Meanwhile, 1.5 trillion m^3 of water is required to deal with pollution caused by capital investment. Surprisingly, governmental activities in China can be emissions intensive. The cumulative COD to support government operations requires a further 1.5 trillion m^3 of water to be resolved.

5 Discussion

China's economy is growing rapidly but at a significant cost in terms of environmental impact and, in particular, available water resources. In response China is placing heavy reliance on advanced technology interventions with its water resources. Indeed, the literature often emphasizes technological innovation as key to addressing the growing water crisis[59]. Our quantitative study has shown that technology advances have driven 6 – 10 times greater efficiency from both production and final demand perspectives. Therefore, efficiency gains are able to offset annual water consumption and pollution emission level increases driven by greater economic growth. But COD effluence have accumulated over years, and these may further contaminate other water resources in the same watersheds and render them 'unavailable' for use for the foreseeable future[28].

Indeed, cumulative pollution is the major contributor to China's emerging water crisis. Between 1992 and 2007, 225 million tonnes of COD accumulated in Chinese water bodies, which requires fourfold of China's annual water resource yields to dilute it to the minimum regulatory re-use standard. Dilution water requirements provides a quantitative measurement of cumulative water pollution to China's hydro-ecosystems. Manufacturing is the largest contributor to cumulative water pollution. In particular, food processing, paper production and textiles are the main polluting sectors. Products from these industries are supplied domestically for household consumption, but significant amounts are also manufactured for export. The cumulative emissions for export purposes over 1997 – 2007 would require almost China's annual water resources yield to be diluted to the eligible re-use level. The service sector is second to manufacturing in cumulative COD effluence, in particular the health, transportation and retailing sectors. These services are mainly consumed by urban households. Technology could be an effective answer for curbing pollution increase, but stepping back from China's emerging water crisis not only depends on technology improvements, but also on adjustment of industrial structures from current pollution intensive patterns, rigorous regulation and enforcement of waste water discharge standards, as well as market measures such as pricing and taxation "polluter pays" mechanisms. A regional cap on water consumption is urgently needed for sub-national water conservation. Moreover, as the uneven distribution of its physical water resources, virtual water (water embodied in traded goods and services) transfer should be encouraged to alleviate regional water scarcity[18, 60-63].

Ahead of its looming water crisis, China's government is investing heavily in large-scale hydro-engineering infrastructure projects. These projects can only provide maximum benefits when efficient and effective management and monitoring measures are in place. For example, until end of 2013 China has constructed 3,513 wastewater treatment plants across the whole of the country, which connects 99% of total urban areas[64]. The total wastewater treatment capacity has reached 140 million m^3 per day, 47 times larger than the United States' capacity. But these treatment plants are not always fully operational. In 2007, a survey by the Ministry of Environmental Protection in China showed over half of the sampled wastewater treatment plants in the Huai River Basin (North China, water scarce region) are only partially operated while polluting factories have a cap on paying for their pollution related fines at 20,000 Yuan

(~ USD$3,000) per year [65]. A 2011 survey in Henan Province (Central China) showed there are some 248 wastewater treatment plants running at only 2% of capacity[64]. The reason is that those plants are state property, requiring public funds from local councils for operation. Reduced operation saves costs so as to contribute to local GDP growth[65]. Therefore, a restructuring of the incentive system of local government is urgently required[66]. Market incentives are key to water management[67]. Flat tariff structures for both water usage and emissions are in use for Chinese industry, but these should be urgently changed.

Finally, China should encourage more water saving consumption by urban households and increase the share of high value added exports which are less water- and COD-intensive during production processes[60]. These would directly tackle the core contributors to cumulative pollution that are the cause of China's emerging water crisis.

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