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The water footprint of food and cooking fuel: A case study of self-sufficient rural India

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ABSTRACT

Water is a basic resource for food and fuelwood production. In general, people in rural areas of India consume carbohydrate rich staples with small amounts of animal foods. They mostly depend upon fuelwood for cooking. This study assesses the WFs for food and fuel consumption in rural India. The research question is: What is the green, blue and grey water footprint (WF) of food and cooking fuel consumption per province in rural India (m^3/cap/year). It used the WF method for the quantification. Data on food and fuelwood consumption were derived from the National Sample Survey (2011–12). Foods were categorized into 6 groups: 1. *Rice*; 2. *Wheat*; 3. *Oils and fats*; 4. *Milk*; 5. *Other animal foods*; and 6. *Others*. Cooking fuel includes: 1. *Fuelwood*; 2. *Kerosene* and 3. *LPG*. Data related to WFs of food were derived from literature reviews and in case of fuelwood, the WFs were calculated for all the provinces of India. Finally, the total WF of per capita consumption is calculated by adding the WF of food and fuelwood. The result shows that there is a large variation in the green, blue and grey WFs for food consumption across the provinces of India. The average WF for food consumption is about 800 m^3/cap/year and for fuelwood is 1630 m^3/cap/year. Rice and wheat dominate the green, blue and grey WFs for food, with variations among the provinces. The green WF of rice is larger than the green WF of wheat, while wheat has a larger blue WF. For cooking fuel, the average WF of fuelwood is much larger than the WF of fossil based cooking fuels. The total WF for fuelwood is twice the WF for food, showing that in rural areas of developing countries, fuelwood is water intensive with large impact on freshwater resources. Future prospects of increasing consumption of animal products will increase WFs. However, if also cooking fuel is considered, switching to fossil cooking fuel lowers WFs far more and compensates the increase due to larger animal food consumption. The trends for cooking fuel found in India might also be relevant for other developing countries.

1. Introduction

Freshwater is a renewable but finite natural resource, with limited availability, often causing competition among its users (Hoekstra and Wiedmann, 2014). Freshwater availability varies across regions and in time (Alcamo et al., 2008). In general, all problems of freshwater over-exploitation and pollution relate to human consumption (Hoekstra, 2013). To visualize the relationship between consumption of goods and freshwater use, Hoekstra (2003) introduced the water footprint (WF) concept which measures the freshwater appropriated to produce goods or services, expressed as a water volume per unit of product. The WF includes three components: green, blue and grey WFs. The green WF is the volume of rainwater consumed during production. The blue WF is an indicator of the consumptive use of fresh surface or groundwater. The grey WF is an indicator of the degree of freshwater pollution and is defined as the amount of freshwater needed to dilute polluted water to accepted water quality standards (Hoekstra et al., 2011) (Schyns et al., 2019).

Globally, the consumption of food dominate the global average annual per capita WF, with cereals contributing 27%, meat 22% and milk 7% (Mekonnen and Hoekstra, 2011a), but differences among countries are large, especially between developed and developing countries. In general, people in developed countries have a large contribution of animal foods to their total food consumption, however, developing countries have food consumption patterns

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Abbreviations

cap	Capita
FW	Fuelwood
ICS	Improved cook stove
LPG	Liquefied Petroleum Gas
MAI	Mean Annual Increment
NSSO	National Sample Survey of Office
TOF	Trees outside forest
WF	Water Footprint

based on carbohydrate rich staple foods with little animal foods (Grigg, 1995) (Winnie Gerbens-Leenes and Mariotti, 2017) (O and "Staple foods: What, 2019). A large fraction of population in developing countries uses inefficient cooking fuel and cookstoves, where fuelwood mostly used for cooking their food and traditional cookstove (Maccarty and Bryden, 2016).

Globally, nearly three billion people reside in rural areas of developing countries, mainly in Asian and African countries (Reddy, 2015). These people live on subsistence farming O and "Forests and energy, 2008) and rely upon traditional biomass, i.e. wood, charcoal, crop residues and animal dung, as their primary cooking fuel (IEA, 2016). In South Asia, 75% of the households use traditional solid fuels for cooking and heating (O and "The World Health Re, 2002) (Health Effects Institute, 2004). Fuelwood projections indicate that the consumption will increase with 24% (Arnold et al., 2006) and also the number of households using fuelwood for cooking will increase (A and "World Energy Outloo, 2010). In these countries, water availability to water requirement for food production might become more problematic than today (Gerten et al., 2011). This is a major concern for rural people, as they depend upon local water availability for their food and fuel ("Rural water deve, 2019).

In the rural areas in India, the dominant fuel for cooking is fuelwood ("Energy Sources of). Adverse effects of fuelwood, used for cooking are well known, especially health effects due to indoor air pollution (Ezzatiet al., 2004) (Smith, 2000), decrease of agricultural productivity, forest degradation "Wood and Wood Prod, 2014) (Miah et al., 2009) and contribution to global warming (Bailiset al., 2007). Although the adverse effects of fuelwood are widely recognized, women in developing countries responsible for cooking tend to prefer traditional cookstoves (Mobarak et al., 2012), which are the most inefficient ones (OA and Global Alliance, 2018).

India is a vast country with the second highest population in the world "Population density a, 2017). Moreover, India suffers from green water scarcity (Schyns et al., 2019). It is a "water stressed" country with 1544 m^3 of water available per capita (Dhawan, 2017). In India, the internal WF dominates the total WF; the external WF contributes only 2%. The average WF in India for agricultural and industrial goods is around 1000 m^3/cap/year (Hoekstra and Chapagain, 2008). This WF includes water for food and electricity, but excludes water for fuelwood, e.g. for cooking. However, in rural areas fuelwood is the main energy source for cooking. Until today, national WFs have included WFs for agricultural and industrial products, but excluded WFs for fuelwood consumption (Gerbens-Leenes et al., 2008). Moreover, studies were done on a national scale, not showing differences between urban and rural consumption (Kampman, 2007). This study aims to give an insight into the water volumes needed to provide both food and cooking fuel in rural India. It answers the following research question: What is the blue, green and grey WF for food and cooking fuel consumption of the rural population per province in India?

Quantification and comparison of per capita WFs for food and fuel consumption at the provincial level provides insight into the WFs for different food and fuel consumption patterns in rural areas of a developing country in Asia. Including fuelwood use in WF assessments shows the large impact of traditional ways of cooking, especially in Asian countries with large rural populations on total WFs.

2. System analysis

2.1. Rural India

About 65% of India's population resides in rural areas (The World Bank and "Rural po, 2017). Almost 80% of the rural population has small landholdings, i.e. less than 2 ha, where they perform agricultural activities (Bisht et al., 2020) (Bishtet al., 2014). Usually, rural households produce their own food (e.g. growing wheat and rice, livestock raising and some fishing) and cooking fuels (e.g. collecting fuelwood or making charcoal from it) (Muller and Yan, 2016). Fuelwood is normally sourced from forests or trees outside forest (TOF) (F and "Status Report on, 2010). The distance of households from a forest matters a lot in the collection of fuelwood (Bošković et al., 2018). A study by Hussain et al. (2017), showed that people prefer to collect fuelwood from forests when it is nearby, otherwise they collect it from TOF areas. They walk to the nearby forest or TOF and chop down the tree branches and carry them back home.

Normally, smallholder farmers produce food for their own consumption. In most cases, surpluses are sold at the local or provincial market (O and "Smallholder farmers) (Poole, 2017). When production is not enough for the province, people tend to buy from the nearby province (Wester et al., 2019). Crop residues and food waste serve as feed for livestock (Wadhwa and Bakshi, 2013). Many rural Indian households own some chickens, goats, dairy cows or buffaloes and pigs (Pica-Ciamarra et al., 2011). They provide some eggs, milk and meat for the household. Due to cultural differences, Hindus consider cows as sacred and Muslims consider pigs as impure, so that cows and pigs are not raised or consumed by the respective populations (Bettencourtet al., 2015). Generally, cattle are used for dairy and draft purposes. They mostly roam around grazing.

2.2. Rural consumption: food and cooking fuel

2.2.1. Food

The food consumption patterns in rural India mainly consists of vegetal foods (Devi et al., 2014) and some animal foods (egg, milk, meat and fish) (Barik, 2016). In India, rice and wheat are the main staple foods, with consumption variation throughout the provinces (Alae-Carewet al., 2019). In some provinces, there is a substantial milk consumption (Satijaet al., 2013). In general, rural households have more diversified diets than urban households, because besides wheat and rice, they also consume substantial amounts of pulses and legumes (Rao et al., 2018). However, the consumption of processed foods is negligible (Mor and Sethia, 2018). In India, fruit and vegetable consumption is small in rural areas, due to limited availability (Kanungsukkasemet al., 2009). For instance, people consume seasonal or local fruits and vegetables available in the province.

2.2.2. Cooking fuel

Rural households mostly use traditional energy carriers for cooking, i.e. fuelwood, charcoal and cow manure (Ranjan and Singh, 2017) and some LPG and kerosene (Central Bureau of Statist, 2012) (O and "Smallholder farmers, 2002) and traditional cookstoves (often a 3-stone open fire). Due to the small heating value of fuelwood and low efficiency of the traditional cookstove (Pandey and Chaubal, 2011), it is an energy inefficient way of cooking and most of the heat is lost to the surroundings. A low-income is an important factor for using a traditional cooking method (Patel et al., 2016). Traditional cookstoves also provide room heating, which encourages rural people living in high altitudes to use them.

2.3. Water situation in rural India

Water is an important resource for food and fuel production (water et al., 2019). India is not a water rich country (Dhawan, 2017). Annual average precipitation is about 1170 mm, of which 75% falls in the 4 months of the monsoon (Aquastat, 2012). Due to spatial and temporal variability of rainfall, there is large variation of water availability among provinces (Dhawan, 2017). In some provinces groundwater is abundant and in others it is scarce. India completely depends upon internal water resources, where more than 62% of irrigated water and 85% of drinking water are sourced from groundwater (O and "-O's In, 2016), making India one of the largest user of groundwater in the world (Greenet al., 2018). Important crops in India, like rice and wheat, but also fuelwood for cooking, are water intensive (water et al., 2019).

Fig. 1 gives an example of green, blue and grey WFs for rice and wheat per province, showing the large differences among provinces in India.

The green WF of rice varies between 1200 and 2400 m^3/ton, except for the province Tamil Nadu in the south where the green WF is smaller (1187 m^3/ton). The blue WF of rice is small in central and north-east India, showing that rice requires little irrigation because it is mostly grown during the monsoon season. The grey WF is almost the same everywhere, indicating similar amounts of fertilizer use. Fig. 1 shows the small green and large blue WF of wheat in central India, indicating that the water requirement of wheat is for a large share met through irrigation. Wheat needs irrigation as it is grown outside the monsoon period (Daviset al., 2018). The grey WF for wheat is relatively large in the two southern provinces i.e. Kerala and Tamil Nadu.

3. Methods and data

The assessment of the WF of food and cooking fuel for rural India includes three steps. Step 1 collects consumption data of food and cooking fuel; Step 2 comprises two sub-steps: collecting WF data of food items and cooking fuel (kerosene and LPG) and the estimation of the WF of fuelwood; Step 3 assesses the WF of individual food and fuel consumption in rural India. The assessment is done for all the 35 provinces of India of six regions: north, west, south, east, central and north-east. Annexure A (Table A1) shows the 35 provinces and regions.

Table 1
Water footprint (WF) of kerosene and LPG in (m^3/ton) (Source (Francke and Castro, 2013) (Bosman, 2016):).
(b) Estimation of WF of fuelwood

	WF (m^3/ton)			WF (m^3/ton)	
Kerosene	Blue	2.89	LPG	Blue	2.69
	Grey	2.89		Grey	2.89

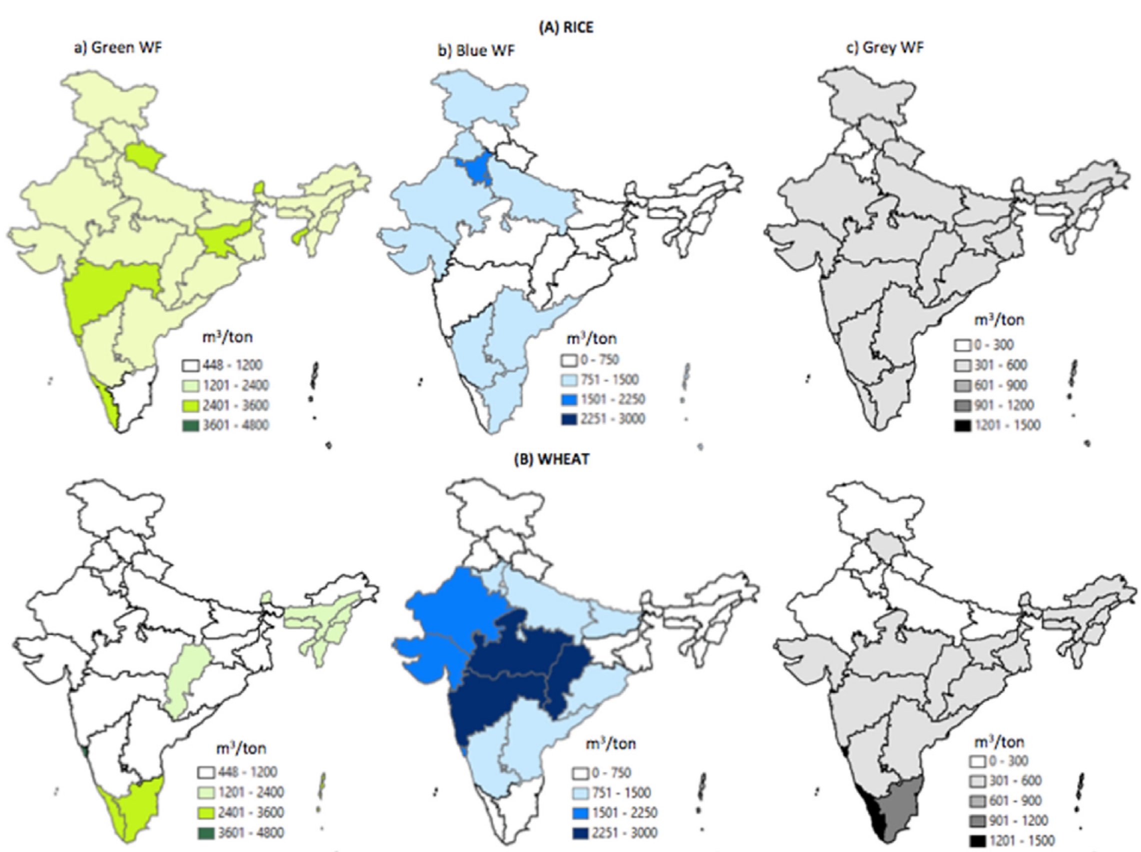

Fig. 1. Green, blue and grey WF of (A) rice and (B) wheat (in m^3/ton) across all the provinces of India. Water footprint data were taken from Mekonnen and Hoekstra (Mekonnen and Hoekstra, 2010a). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.1. Step 1: collecting consumption data of food and cooking fuel

Step 1 collects consumption data of food and cooking fuel of rural households per province in India. The National Sample Survey of Consumption Expenditure in India (NSSO Round 68, 2011–12) ("Household Consumpt, 2014) with information from 100,000 rural and urban households in India provides per capita consumption data of food and cooking fuel purchased and produced per province. The main reason of using this dataset is that, it provided the most recent consumption data available for rural and urban households in India. We derived consumption data on food and cooking fuel for rural India from the survey ("Household Consumpt, 2014).

We categorized the foods into 6 groups: 1. *Rice*; 2. *Wheat*; 3. *Oils and fats* (coconut oil, groundnut oil, sunflower seed oil, sesame oil); 4. *Milk*; 5. *Other animal foods* (pork, beef, goat meat and egg) *and fish*; and 6. *Others*. The "others" group includes coarse cereals (barley, maize, millet and sorghum), pulses and legumes (beans, kidney beans, peas, chickpeas, pigeon peas, lentils, urd and mung beans), vegetables (cabbage, lettuce, tomato, cauliflower, pumpkin, squash, gourd, cucumber, aubergine, onion, beans, peas, carrots, turnip and okra), spices (ginger, garlic, nutmeg, coriander, turmeric, pepper, capsicum, curry, anise), potatoes, fruits (coconut, banana, orange, lemons and limes, grapefruit, apple, grapes, watermelon, guava, pineapple, papaya), sugar and beverages (tea and coffee).

The survey provided energy and fuel consumption data for cooking, lighting and household appliances for rural and urban areas. Data on fuel for cooking include consumption of coke and coal, fuelwood, LPG, cow manure, kerosene, charcoal, biogas and electricity. Household consumption of fuels for cooking energy sources is provided in Annexure C (Fig. C1).

3.2. Step 2

(a) Collecting water footprint data of food items and cooking fuel (kerosene & LPG)

Mekonnen and Hoekstra (2010a) have quantified the WF of crops using a grid-based dynamic water balance model that considers local climate, soil factors and nitrogen use for the years 1996–2005. For India, WFs were available at the provincial level. In our study, we assume that pigs, goats and chicken were fed from household food waste and crop residues. To avoid double counting, we assumed that residues are enough for the small livestock herd and we assumed that WFs of meat and eggs are zero. For dairy cows, we assumed that milk is produced in a grazing production system. Feeding only crop residues to dairy cows is not enough to produce milk. For the assessment of the WFs of milk consumption, we derived national average WF data for a grazing production system in India from Mekonnen and Hoekstra (2010b). For fish, we assumed that it is taken from open lakes or ponds without supplementary feed. Therefore, the WF's of fish is considered zero.

For spices and fruits, we calculated the average WF using the separate WFs of foods in the group. For some provinces, WF data for few food items were not available because there is no production. When there is consumption, we assumed that the foods were bought in the nearest provinces. This is for example the case for the Lakshadweep, Andaman and Nicobar Islands. For the other provinces without production, we took the WF data of the nearby provinces using a weighing factor based on rural population per province assuming there is a linear relation between rural population size and the total production. We calculated the weighted average of WF of food items bought in a province, $\mathrm{WF_{fd.avg}}$, as:

$$\mathrm{WF_{fd.avg}} \cdot = \cdot \sum_{i=0}^{n} \frac{WF_{pri}x_i + WF_{pr2x2} + \ldots + WF_{prn}x_n}{x_i + x_2 + \ldots + x_n} \tag{1}$$

where $\mathrm{WF_{pr}}$ is the WF of a food item in province i (m^3/ton) and x is the weighing factor (i.e. rural population of the province). Data on rural population were taken from the census of India (2011) (Population, 2015).

The production chain of LPG and kerosene is probably the same everywhere, irrespective of physical factors like precipitation or temperature (A and "Report on managin, 2016). Hence, we assumed that the WF of LPG and kerosene is the same for all the provinces. Table 1 shows the blue and grey WF of LPG and kerosene. Data were taken from Francke et al. (Francke and Castro, 2013) and Bosman et al. (Bosman, 2016).

The WF for fuelwood was estimated in three steps: First, we assessed the WF of the harvested wood, followed by the second step where we quantified the green and blue WF. In the third step, we assessed the WF per unit of fuelwood (m^3/GJ).

(i) Assessing the WF of harvested wood

The WF of harvested wood is assessed by using the method developed by Van Oel and Hoekstra (van Oel and Hoekstra, 2012). Normally, the calculation uses the actual amount of roundwood harvested. In this study, we assumed that all the wood is harvested from the annual growth of the forest (m^3/ha/year) (Blanchez, 1997), the Mean annual increment (MAI) (m^3/ha/year).[1] The water volume allocated to fuelwood production $\mathrm{WF_{fw}}$ [s,t], for "s" provinces in the year "t", was calculated as:

$$\mathrm{WF_{fw}} \cdot [\mathrm{s,t}] \cdot = \cdot \frac{\left(E_{act}[s,t] \times A_{fw}[s,t]\right) + (MAI[s,t] \times f_w[s])}{MAI[s,t]} \cdot \times \mathrm{f_v} \cdot [\mathrm{s,t}] \tag{2}$$

where E_{act} is the actual forest evaporation (m/y), A_{fw} is the area used for fuelwood production (m^2), f_w is the volumetric moisture content of freshly harvested wood (m^3 water/m^3 wood) and f_v is a dimensionless fraction that represents the relative value of harvested fuelwood production compared to the value of other ecosystem services provided by the forest. In this study, we assumed that fuelwood is the primary product of a forest and that growth is equal to the harvest. Thus, the value fraction is equal to 1.

The E_{act} was estimated based on annual temperature (°*C*) and precipitation (m/y). While taking the annual data for temperature and precipitation, we ensured that the seasonal monthly average data was taken, as seasonal variability affects the blue and green water required by fuelwood. For the north-east region, we clustered temperature and precipitation data for the provinces Sikkim, Tripura, Nagaland, Manipur, Meghalaya and Arunachal Pradesh and considered the clustered provinces as one province. Temperature and precipitation data were not available for 8 provinces (Chandigarh, Delhi, Daman and Diu, Dadra and Nagar Haveli, Goa, Andaman and Nicobar Islands, Lakshadweep and Puducherry). For these provinces, we took the WF data of fuelwood from the nearby provinces. MAI data were taken from Das and Nonhebel (2019). For more details on $\mathrm{W_{fw}}$ see Annexure D, Section D.1.

(ii) Quantifying the green and blue WF

[1] Mean annual increment: The annual increase in the volume of wood grown per hectare is termed mean annual increment (MAI) (Das and Nonhebel, 2019).

The green and blue WF was quantified by applying a fraction, where the part of water use originates from the capillary rise (f_{blue}) from Schyns et al. (2017a):

$$WF_{fw \cdot green} \cdot [s,t] \cdot = \cdot WF_{fw} \cdot [s,t] \cdot \times \cdot (1 - \cdot f_{blue} \cdot [s,t]) \quad (3)$$

$$WF_{fw.blue} \cdot [s,t] \cdot = \cdot WF_{fw} \cdot [s,t] \cdot \times \cdot f_{blue} \cdot [s,t] \quad (4)$$

where $WF_{fw \cdot green}$ is the green WF and $WF_{fw \cdot blue}$ is the blue WF for the harvested fuelwood. The f_{blue} is the capillary rise (for details, see Annexure C, Section C.1).

(iii) Estimation of the WF per unit of fuelwood

The WF per unit of fuelwood (WF_p) was estimated by multiplying WF_{fw} with a conversion factor ($f_{conversion}$) (i.e. the amount of wood (m^3) required to produce energy (GJ) for cooking). The WF of the final product (i.e. fuelwood) was expressed in m^3/GJ. The WF per unit of fuelwood, WF_p, was calculated as:

$$WF_p \cdot = \cdot WF_{fw} \cdot \times \cdot f_{conversion} \quad (5)$$

The conversion factor, $f_{conversion}$, was calculated as:

$$f_{conversion} = \cdot \frac{1}{Wood\ density \times Heating\ value} \quad (6)$$

Data on wood density were taken from (Gerbens-Leenes et al., 2008). The heating value of fuelwood was assumed to be 14 MJ/kg dry weight (Bhatt et al., 2010).

3.3. Step 3: assessing the WF of individual food and fuel consumption

3.3.1. Food

The assessment of the WF of food consumption comprises of two stages. In the stage one, we calculated the direct WF, which includes drinking, cooking and washing utensils. The blue water for drinking is the amount of water a person drinks per day. For cooking, it includes the water used to prepare food. Annexure G gives the details.

Stage two calculated the blue, green and grey WF for individual food consumption per province per year, $WF_{f,i}$ estimated by combining individual consumption (from section 3.1) with the WF data of food items (from section 3.2.a) per province:

$$WF_{f,i} \cdot = \cdot I_f \cdot \times \cdot WF_f \quad (7.a)$$

where I_f is the individual consumption (t/cap/yr) and WF_f is the WF per unit of food. The blue WF includes food items as well as direct blue water consumption (i.e. drinking, cooking and washing utensils).

3.3.2. Cooking fuel

For cooking fuel, the WFs (blue, green and grey) for fuelwood and fossil fuel differ. For fuelwood, based on Schyns et al. (2017b) we considered only the consumptive part i.e. the blue and green WF, and excluded the grey WF related to water pollution. As explained by Chiu and Wu (2013), forests require a negligible amount of fertilizer as its own ecosystem is more than enough for its growth. However, in case of fossil fuels like LPG and kerosene, blue and grey water are the major components. The WF for cooking fuel, $WF_{c,i}$ (m^3/cap/year), was calculated as:

$$WF_{c,i} \cdot = \cdot I_c \cdot \times \cdot WF_p \quad (7.b)$$

where i denotes the blue, green and grey WF and c cooking fuel consumption, I_c is the individual consumption (MJ/cap/year) and WF_p is the WF per unit of cooking fuel.

The blue and green WFs for cooking fuel were calculated by combining individual fuel consumption (MJ/cap/year) (from section 3.1 where we collected the consumption value (ton/cap/yr), which was then multiplied by the heating value of cooking fuel) with the WFs for fuelwood (from section 3.2.b) and other cooking fuels (from section 3.2.a).

4. Results

4.1. Total green, blue and grey WF for food and cooking fuel consumption

4.1.1. Water footprint for food consumption

Fig. 2 shows the contribution of rice, wheat, oil and fats, other (coarse cereals, pulses & legumes, vegetables, spices, potatoes, fruits, sugar and beverages) and milk to the total water footprint (WF) of an individual in rural India.

Rice, wheat, oils and fats accounts for the largest fraction of the total WF in most of the provinces of rural India. However, in the north, west and southern part, also other food item groups have a relevant contribution to the total WF. Some provinces in the north like Punjab and Haryana have a relatively small contribution from the rice WF, but milk has a relatively large contribution to the total WF. Fig. 2 shows that there is a significant variation in the contribution of rice and wheat to the total WFs among the provinces. Most of the provinces in the north and west have larger wheat WF contributions than rice. However, there are some exceptions. Provinces like Madhya Pradesh and Puducherry in the central and southern part respectively, where the wheat WF contribution is larger than the rice contribution. This is due to the combination of large wheat WF and high wheat consumption. In the north-eastern provinces, rice and wheat WFs together contribute 70% to the total WF and 10–20% of the WF relates to wheat consumption. In the north-east region, the contribution of wheat is almost negligible as the consumption is relatively small. Fig. 3 shows the annual green, blue and grey WFs for rice and wheat consumption of an individual in rural India.

Although the green WF for rice is relatively large in all the provinces in India (Fig. 1), Fig. 3 shows that the green WF is largest in the eastern part of the country where the consumption is larger. In the northern and southern regions, the blue WF for rice is larger than in the other regions, due to rice irrigation. The green WF for wheat consumption is small in comparison with the green WF of rice consumption. However, the blue and grey WF for wheat consumption is relatively large in the west and central region. This is caused by a combination of large specific blue and grey WFs and large wheat consumption. For instance, the blue WF of wheat in Rajasthan is about 1704 m^3/ton and the consumption is about 0.11 ton/cap/y making it a total WF of about 190 m^3/cap/year. However, in case of Maharashtra, the blue WF of wheat is 2711 m^3/ton and the consumption is 0.05 ton/cap/year resulting in a blue WF of 140 m^3/cap/year. Harris et al. (2017) did a regional study on WF of Indian diets for north, south, east and west India, where the wheat consumption for west India is about 0.11 ton/cap/year, which is very much relatable to our consumption data. The study concluded that wheat and rice contribute about 31% and 19% to the blue WF of food consumption in India.

Fig. 4 shows the total green, blue and grey WF for annual per capita food consumption. There are large differences among green,

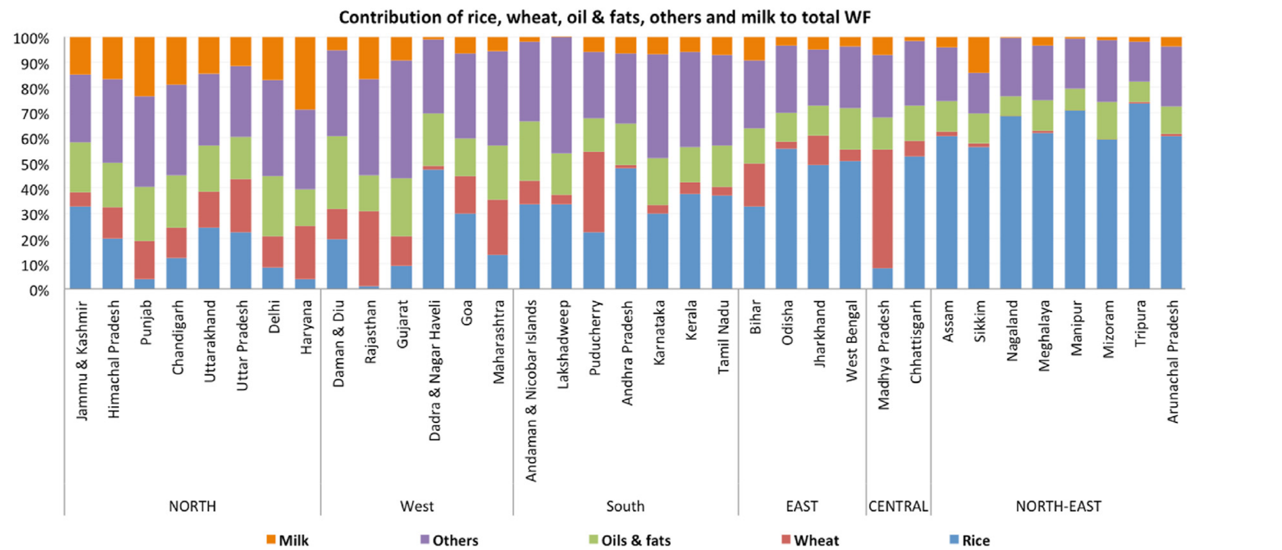

Fig. 2. Contribution of rice, wheat, oil & fats, others (*coarse cereals, pulses & legumes, vegetables, spices, potatoes, fruits, sugar and beverages*) and milk to the total water footprint.

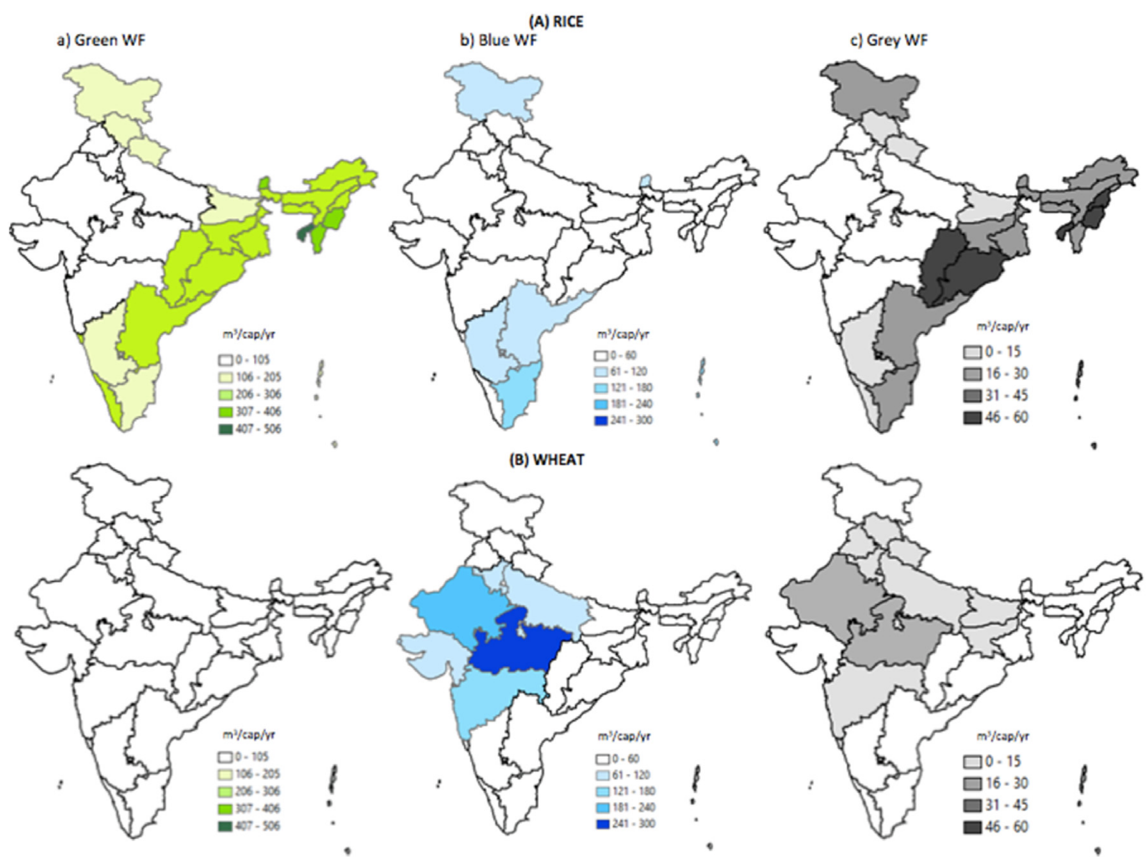

Fig. 3. Green, blue and grey water footprint (WF) for (A) rice and (B) wheat consumption in rural India (m^3/cap/year). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

blue and grey WFs across the provinces. The green WF ranges between 380 and 900 m^3/cap/yr. The green WF is large mainly in the provinces located in the north, south and west regions. One of the main reasons is the high consumption of dairy in those regions. Fig. 3 showed that in the west region the green WF is not large due to rice and wheat consumption. Oils and fats and other food items have more impact on the green WF in those provinces. Fig. 4 shows that a part of north-east India has a relatively large green WF, Fig. 3 showed that this is due to rice consumption.

The blue WF ranges from 6 m^3/cap/year in the north-east region to 334 m^3/cap/year in the central and west region. Blue WFs are largest in central India, and in some provinces in the southern region. The variations are quite large across the provinces. For instance, Madhya Pradesh located in the central region has the

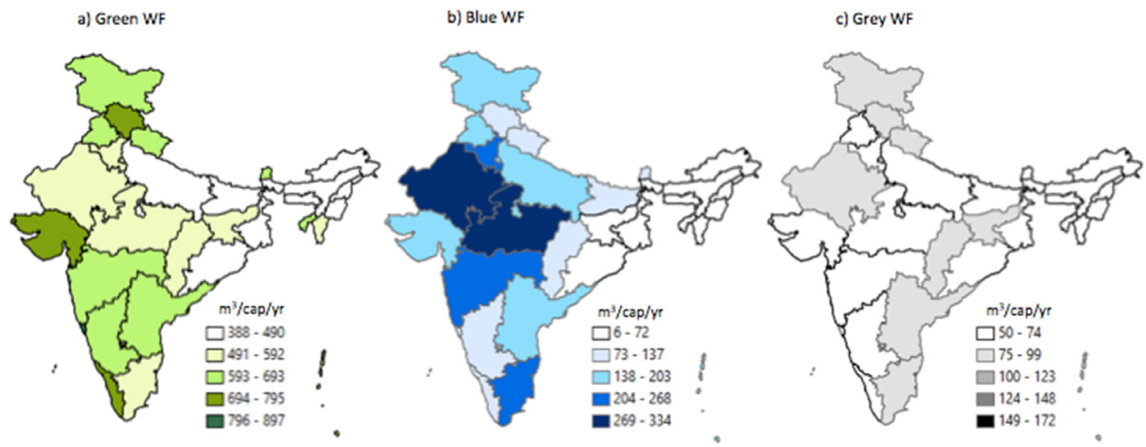

Fig. 4. Total green, blue and grey water footprint (WF) for per capita food consumption in rural India (m^3/cap/year). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

largest blue WF (334 m^3/cap/year), where the blue WF from wheat consumption contributes 87%. The smallest blue WF is in Mizoram (6 m^3/cap/year). The blue WF is relatively small in the east and north-east regions, due to large rain fed rice consumption. Large blue WFs in the southern province, especially Tamil Nadu and Andhra Pradesh are caused by irrigated rice consumption. However, the reason for the large blue WF in the central region (i.e. Madhya Pradesh) and western region (i.e. Rajasthan and Maharshtra), is due to large irrigated wheat consumption. The grey WF ranges from 50 to 170 m^3/cap/year. Most of the provinces lie in the range of 50–100 m^3/cap/year.

4.1.2. Water footprint for fuelwood consumption

Fig. 5 shows the green, blue and grey WF of fuelwood per unit of energy in rural India. There are large variations among the provinces for both green and blue WFs. The green WF for fuelwood is larger in the central, east and north-east regions. The largest green WF is in Assam (607 m^3/GJ). The green WF for fuelwood in the south lies between 15 and 130 m^3/GJ, except, for Kerala, which has a large green WF of about 563 m^3/GJ.

The blue WF is evident in almost all the provinces of India, except in a few provinces like Punjab and Haryana in the north and all the provinces in the north-eastern region where the WF is relatively small. The blue WF in some of the provinces in the west and central regions of India is extremely large. For instance, Rajasthan province in the west regions has a large blue WF of about 718 m^3/GJ and a small green WF of about 132 m^3/GJ. This is due to low groundwater levels in that province, which eventually increases the capillary rise (f_{blue}) (Suhag, 2016). However, few provinces have relatively large green WFs and small blue WFs, which means that one compensates for the other. For example, the Assam province, which has a large green WF (607 m^3/GJ), eventually has a small blue WF (8 m^3/GJ). However, some provinces have both large blue and green WFs like Odisha and Madhya Pradesh, both blue and green WFs are large. This indicates that those provinces experience high forest evaporation rates and small fuelwood production. Fig. 6 shows the annual green and blue WF of individual fuelwood consumption per province in rural India.

The green WF for fuelwood consumption is largest in the Assam province (3048 m^3/cap/year), followed by the Kerala province in

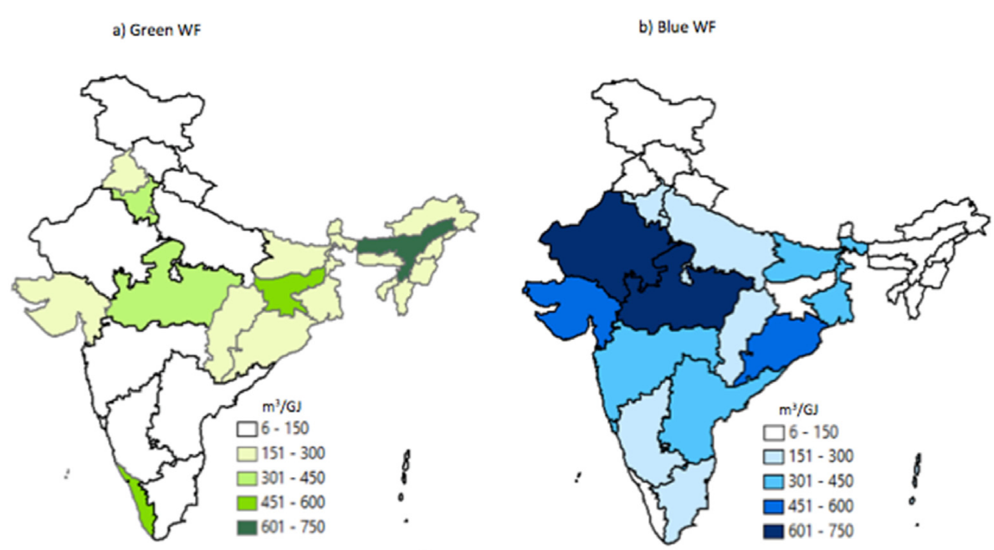

Fig. 5. Green and blue water footprint of fuelwood per unit of energy in rural India. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

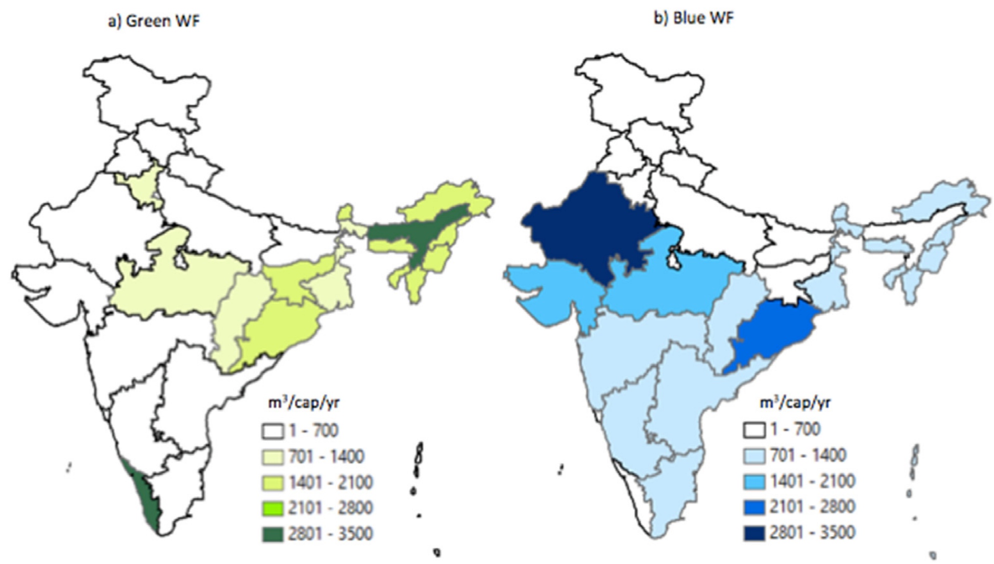

Fig. 6. Green and blue water footprint (WF) for fuelwood consumption in rural India. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the southern region (3066 m^3/cap/year). However, there is also a reasonable amount of green WF in the central and east regions. The blue WF is relatively large in the western province, especially in Rajasthan (3444 m^3/cap/year), followed by Gujarat (1973 m^3/cap/year). However, besides the northern provinces, fuelwood consumption in the other provinces generates a blue WF.

4.2. Total water footprint of food and fuelwood

Fig. 7 shows the total green, blue and grey WF of food and cooking fuel across all the rural regions of India. The cooking fuel includes WFs of fuelwood, kerosene and LPG.

Fig. 7 shows that if cooking fuel are included in the assessment of WFs for food in rural India, it dominates the total WF. Except in northern India, the WF for cooking fuel is larger than for food consumption. The WF for cooking fuel is relatively small in the northern region where the consumption of fuelwood is relatively small due to the use of kerosene and LPG. Fig. 7 also shows that there is a large variation in the green, blue and grey WF for cooking fuel. For instance, the blue WF is relatively large in the western region and relatively small in the north-eastern region. Due to the inclusion of kerosene and LPG, there is a small grey WF for cooking fuel. However, in comparison with the green and blue WF it is almost negligible.

In case of food consumption, in all regions, WFs are dominated by green WFs and despite differences in consumption variation of total WFs for food consumption is small. It shows that in rural India, the blue WF of food consumption is relatively small compared to the blue WF of fuelwood consumption.

5. Discussion

5.1. Food consumption

An earlier study, which included both rural and urban population, has calculated the average per capita WFs for India of 1089 m^3/cap/yr, including WFs for food, industry and domestic services (Mekonnen and Hoekstra, 2011b). This study shows that the total WF for food consumption of an average rural Indian is about 800 m^3/cap/yr. According to Harris et al. (2017), the average green WF for food consumption in India is about 708 m^3/cap/yr, the blue WF is 213 and the grey WF is 93 m^3/cap/yr. However, our study for rural India finds smaller WFs. The green WF for rural India is 15% smaller, the blue WF is almost half and the grey WF is 19% smaller

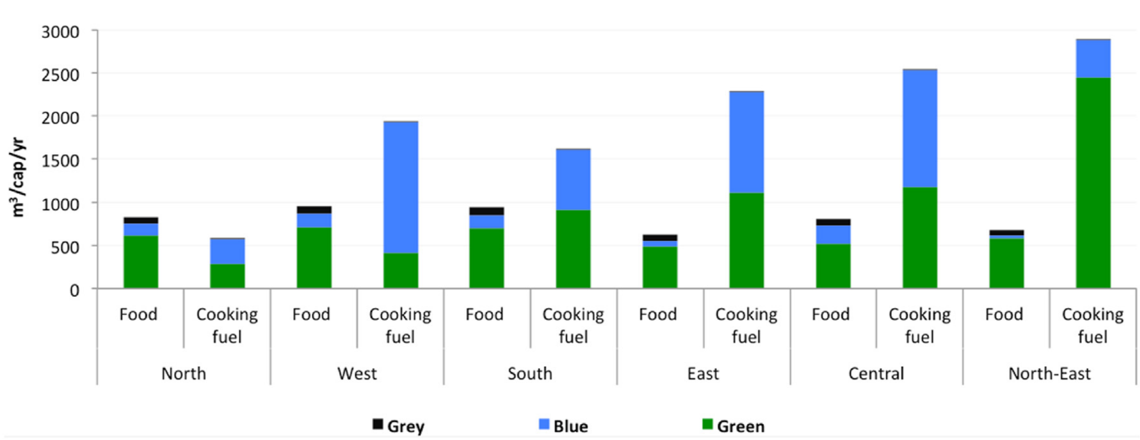

Fig. 7. Total water footprint for food and cooking fuel across all the regions of India.

than the national average. This probably has to do with the distinction we could make between food consumption of rural and urban populations. Both studies, i.e. Harris et al. (2017) and this study, shows that the main staple cereals are rice and wheat. However, we found that rice consumption in rural areas in India is about 53% larger than consumption in urban areas as reported by Harris et al. (2017).

Another difference with the study of Harris et al. is that we used consumption data of national food and fuelwood surveys rather than national supply data from the FAO. It is possible that under-reporting has occurred so that our study might underestimate WFs. We also assumed that livestock is fed residues from agriculture and households, so that the WFs of meat and eggs are allocated to the food to avoid double counting. However, meat and egg consumption in rural India is so small that the impact is negligible. In some provinces people consume substantial amounts of milk though. Because of large consumption, we assumed that residues are not enough for milking cows and we adopted WFs for milk from Mekonnen and Hoekstra (2012).

Our analysis assessed the WFs of rural India assuming that people are self-sufficient and that trade only occurs when there is no production in the province itself, e.g. the case of the Indian islands. There is food trade in India though, e.g. there is a net virtual water flow related to the food trade from the north to the provinces in the east of the country (Kampman, 2007). If the rural population consumes foods produced locally, the virtual water trade reflects urban consumption.

The WF study by Mekonnen and Hoekstra (2010a), includes water consumption for agricultural production giving WFs per crop per province per country. That database can be applied to assess WFs related to food consumption, e.g. for individuals, households or countries. In this study, we also incorporated the water requirement for cooking activities, drinking and washing utensils, so as to include the process from farm to the dining table. However, we found that the direct blue WF is almost negligible (i.e. 6 m^3/cap/yr) compared to the WF for food consumption.

5.2. Water footprints for fuelwood

The average WF for cooking is 1600 m^3/cap/year, but variation among provinces is large ranging from 2 to 4000 m^3/cap/year caused by differences in individual consumption and fuel WFs. Although wood is the main cooking fuel, provinces in the north use a substantial amount of kerosene and LPG with smaller WFs, reducing the cooking WF.

The mean actual forest evaporation plays a major role in the WF of fuelwood, as it affects the tree water requirements. The average mean forest evaporation is 940 mm/year (Annexure H, Table H.1) giving an average WF of wood of 560 m^3/GJ, about four times larger than the WF calculated by Schyns et al. (Schyns and Vanham, 2019) of 122 m^3/GJ. This large difference could be due to the difference in assumptions. Schyns et al. (Schyns and Vanham, 2019) have taken the mean forest evaporation in the sub-tropics of 800 mm/year for their calculation (Schyns et al., 2017b), which is 15% smaller than our estimate. Van Oel et al. (van Oel and Hoekstra, 2012) have shown that for Eucalyptus in India evaporation is even smaller, i.e. 500 mm/year. Differences in evaporation cannot explain the large WF differences among studies though. Another reason is the different assumption of wood harvest. Our study assumed that only the average annual growing part of the tree (MAI) is harvested for cooking fuel, which generates a smaller yield than assumed by Schyns et al. (Schyns and Vanham, 2019).

In our study, we assumed that the fuelwood is collected from forests, as there is no clear indication in the NSSO report on the source of fuelwood. Normally, rural people also collect fuelwood from trees outside the forest (TOF), because of its easy accessibility. MAI is an important variable in the WF calculation (see eq. (1)). Normally, WFs are expressed per unit of yield, i.e. the yield of fuelwood is inversely related to the fuelwood WF. Das et al. (Das and Nonhebel, 2019) have shown that the TOF fuelwood yield is half the wood yield from a forest. Hence, if the fuelwood were collected from TOF the WF would be twice the WF of wood from forests. Consequently, assuming that all wood is from forests might underestimate the WF for cooking.

An easy option to decrease the WFs for cooking is to opt for efficient use of cooking fuel. For instance, inefficient cookstoves like traditional open-fire cookstoves are mostly used in rural India, and requires far more fuelwood than improved cookstoves (ICS) (Dresen et al., 2014). Das et al. (2018) have shown that the fuelwood demand decreases by 70% if ICS is used for cooking.

Fig. 6 shows that northern India has a smaller WF for fuelwood than the other provinces, due to kerosene and LPG use. Chandigarh province has the largest use of LPG and kerosene (1612 MJ/cap/yr). If all provinces in the north-east use 1612 MJ/cap/yr from LPG and kerosene and the remaining energy from fuelwood the WF decreases by 67%. This example shows that LPG and kerosene are far better from a water saving perspective.

This study on WF analysis for food and fuel consumption is exclusively based on the WF per unit of product, which is multiplied with the consumption data collected from the NSSO report. The main insight of this study is that the fuelwood has a large WF per unit of product than the food. Normally, the WF of per unit of product (either food or fuel) will hardly change over a period of time. However, the consumption of food and fuel can change over a year depending upon income and accessibility (Cheng and Urpelainen, 2014). Thus, the data from NSSO does not make much impact on the WF analysis.

5.3. The relevance of including cooking

Studies assessing WFs of food consumption generally combine data on product WFs, for example from (Mekonnen and Hoekstra, 2010a), with data on consumption of specific foods. Since WFs are dominated by agricultural water consumption, leaving water consumption in the rest of the chain out does not change the WF much. In our study we also included water consumption for cooking which is only 0.75% of the total WF and therefore negligible. However, another important input for a final meal available for human consumption is energy. Especially developing countries like India depend on fuelwood for cooking, an energy source with a relatively large WF. Water footprint assessments include four distinct phases, (i) setting goals and scope; (ii) the actual WF accounting; (iii) sustainability assessment; and (iv) response formulation (Hoekstra et al., 2011). To find ways to decrease WFs related to food consumption in India in phase iv, we expanded the system boundary of phase ii normally applied in WF assessments by also including the energy component. By doing so we are able to indicate important options for developing countries to decrease WFs, i.e. decrease fuelwood use and replace traditional cookstoves by more modern ones. Changing food consumption patterns in developed countries by replacing foods with large WFs, mainly animal foods, by foods from vegetal origin with smaller WFs (Mekonnen and Hoekstra, 2010a) (Mekonnen and Hoekstra, 2010b) to decrease WFs are not an option for developing countries, because consumption patterns include little meat. However a shift towards other cooking fuels might substantially decrease the total WF for food.

5.4. Trends

If rural people in India follow the development observed in other rapidly developing countries, e.g. in China, towards a food consumption pattern with more livestock foods (Alae-Carewet al., 2019), the total WF will increase. Our study indicated that in rural India the WF related to food is dominated by the use of cooking fuel. If also the perspective of cooking is included, more efficient cookstoves, or a shift to other ways of cooking that go along with rural development decrease the total WF. Considering a 70% decrease of fuelwood demand by using ICS, we show that the WF will decrease to 507 m^3/cap/year (i.e. about 70% decrease). Hence, this might be the case in other developing countries with large use of fuelwood and traditional cookstoves too.

6. Conclusion

This study showed the importance of including the WFs of cooking fuel in WF analysis. In self-sufficient rural India, the total WF for cooking, mainly due to the use of fuelwood is twice the WF for food, showing that in the rural areas of India, a developing country, especially fuelwood is water intensive with large impact on freshwater resources. In rural India, the average WF for food is 800 m^3/cap/year and for fuelwood m^3/cap/year. Green water accounts for 57%, blue water for 30% and grey water for 3% of the total WF of food. Rice and wheat are the main staple foods with large WFs and large contribution to total WFs of food consumption.

Rice, wheat, oils and fats contribute most to the total WF of food in rural India. In the north-eastern provinces, rice and wheat WFs together contribute 70% to the total WF. 10–20% of the WF related to wheat consumption. In Madhya Pradesh and Puducherry, in the central and southern part of India, the wheat WF contribution is larger than the rice WF contribution. This is due to the combination of large wheat WF and large wheat consumption. The blue WF ranges from 6 m^3/cap/year in the north-east to 334 m^3/cap/year in the central and west region. Blue WFs for food are largest in central India, and in some provinces in the south region. Variations are large among the provinces. Madhya Pradesh has the largest blue WF for food (334 m^3/cap/year) and the blue WF from wheat contributes 87%. The smallest blue WF is in Mizoram (6 m^3/cap/year). The relatively small blue WF in the east and north-east is due to large rain fed rice consumption. Large blue WFs in the southern provinces are caused by irrigated rice consumption.

For cooking fuel, the average WF of fuelwood is much larger than the WF of fossil fuels. There is a large variation among the WFs for food and fuel across the provinces. The green WF for fuelwood consumption is largest in the south and north-east provinces (2800–3500 m^3/cap/year. However, there is also a relatively large green WF in the central and east regions. The blue WF is relatively large in the western regions.

For food consumption, in all Indian regions, WFs are dominated by green WFs and despite the differences in consumption, variation of total WFs for food consumption is small. In rural India, the blue WF of food consumption is relatively small compared to the blue WF for fuelwood consumption.

For rural India, future prospects of increasing consumption of animal foods will increase the WF. However, if also cooking fuel is considered, switching to fossil based cooking fuel will lower WFs far more and can compensate an eventual increase of larger consumption of animal foods. The trends found for India might also be relevant for other developing countries.

CRediT authorship contribution statement

K. Das: Conceptualization, Methodology, Formal analysis, Writing - original draft. **P.W. Gerbens-Leenes:** Conceptualization, Methodology, Writing - review & editing, Supervision. **S. Nonhebel:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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