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Water footprint of rice from both production and consumption perspective assessment using remote sensing under subtropical India: A review

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Abstract

Consumptive water footprint (WF) reduction in irrigated crop production is essential given the increasing competition for freshwater. The calculated green, blue and grey water footprints of paddy rice are converted into estimations of the green, blue and grey water footprints of derived rice products on the basis of product and value fractions. International virtual water flows related to trade in rice products are estimated by multiplying trade volumes by their respective water footprints in the exporting countries. Reduction in overall consumptive WF always goes together with an increasing ratio of green to blue water footprint. We take both a production and a consumption perspective. Total *water footprint of rice production* is estimated by aggregating the water footprints per production region and the *water footprint of rice consumption* is estimated by looking in which regions of the world the rice that is consumed in that nation is produced. The water footprint of rice consumption in a nation is calculated by aggregating the water footprints in the regions where the rice consumed in a nation is grown by using a higher spatial resolution. In India water foot print of per unit and total rice production and percolation was 1403 (m^{3}ton^{-1}) and 432.9 (billion m^{3}yr^{-1}). The per-capita water footprint of rice consumption is quite high in Thailand (547 m^{3}cap^{-1}yr^{-1}) compared to India (239 m^{3}cap^{-1}yr^{-1}), with their water footprints related to rice consumption 63,364 and 250,305 (Mm^{3}yr^{-1}), respectively.

Globally, agriculture accounted for about 3,100 billion cubic meters (m^3), or 71%, of water withdrawals in 2005. If there are no efficiency gains, this will increase to 4,500 billion m^3 by 2030. (ii) Industrial withdrawals accounted for 16% of current global demand, growing by 91%, to take 22% of withdrawals in 2030. This growth will mainly come from the PRC, which alone will account for 40% of the additional industrial demand worldwide. (iii) Demand for domestic use will increase from some 600 billion to 840 billion m^3 per year, representing a relative decrease by 2030 as a percentage of total water withdrawal, from 14% to 12%. pectively. The total footprint on India is the largest; a large fraction of it is made up of green water. Remote sensing has long been a useful tool in global applications, since it provides physically-based, worldwide, and consistent spatial information. This review paper discusses the potential of using these techniques in the research field of water management, particularly for ‘Water Footprint’ (WF) studies. In this paper evapo-transpiration, precipitation, water storage, runoff and land use are identified as key variables to potentially be estimated by remote sensing and used for WF assessment.

Keywords: Water footprint, remote sensing, water scarcity, water management

Introduction

One of the important prospects for relieving increasing water scarcity is to reduce the consumptive water use in the agricultural sector, which makes up the largest share in global freshwater consumption (Hoekstra and Mekonnen, 2012) [28]. In crop production substantial gains can be achieved by increasing yield and reducing water losses, with the latter referring to the non-beneficial consumptive water use at field level and the non-recoverable losses at system level (Hoekstra, 2013; Falkenmark and Rockström, 2006) [24, 20]. At field level, the focus is to decrease the field evapo-transpiration (ET) over the growing period per unit of yield (Y), a ratio that is called the consumptive water footprint (WF) (Hoekstra *et al.*, 2011) [35]. Decreasing this ET/Y ratio is the same as increasing the inverse (Y /ET), which is called the water productivity (WP) (Amarasinghe and Smakhtin, 2014) [3]. The soil moisture status in the root zone regulates plant growth and influences ET. Management practices that influence soil moisture include production and consumption practices. The particular water footprint influences the way water is applied, which influences for instance the percentage of surface wetting, which again influences ET (Raes *et al*., 2013) [38]. The particular water footprint strategy applied determines how much and when water is used.

The world is under great pressure to feed nine billion people by 2050. Total evapo-transpiration (ET) from global agricultural land could double in the next 50 years if trends in food consumption and current practices of production continue (de Fraiture *et al*. 2007). With increasing demand from non-agricultural sectors and the uncertainties in water management brought about by climate change, the agricultural sector in many areas will get less water in the future (Bakkes *et al*. 2009) [5]. Together, the increasing demand for water for food production and the limits of the availability of water resources suggest that agriculture must produce more food with less water, that is, make more productive use of water resources (Cai and Sharma 2010) [13]. Changing global climatic patterns coupled with declining per capita availability of surface and ground water resources, stiff competition for scarce water resource from other sectors have made sustainable rice cultivation in the challenges. Recognizing the importance of the facts given, quantification of water balance parameters, particularly water loss into the atmosphere (evapo-transpiration), percolation and seepage under the present management system is necessary to increase water productivity. Therefore, priority is the development of the indices that reflects fresh water resources per unit quantity of agricultural produces from a particular management system. In this regards water footprints which is the “ratio of the volume of consumptive water use to the quantity of produce obtained” can be used to indicate the requirement of direct (the green and blue water footprint) and indirect (the grey water footprint) freshwater resources (Aeschbach-Hertig and Gleeson, 2012; Keys *et al*. 2012; Zang *et al*. 2012) [1, 31, 43].

The water footprint has three components viz., ‘green’, ‘blue’ and ‘grey water foot prints. ‘Green water footprint is the volume of water, received from rain, ‘Blue water’ refers to the volume of irrigated water used from surface and ground water resources, Whereas, ‘grey water’ or polluted water is the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. Lower water footprint of a crop reflects its efficiency to produce more biological yield with less amount of water (Kiptala *et al*., 2014; Curmi *et al*. 2013; Karimi etal. 2013) [32, 16, 30] Figure 1.Rice is the staple food for nearly half of the world’s population, most of who live in developing countries. The crop occupies one-third of the world’s total area planted to cereals and provides 35–60% of the calories consumed by 2.7 billion people. More than 90% of the world’s rice is produced and consumed in Asia (Barker and Herdt 1985, IRRI 1989) [6, 29]. Rice is the most widely grown of all crops under irrigation. More than 80% of the developed freshwater resources in Asia are used for irrigation purposes and more than 90% of the total irrigation water is used for rice production (Bhuiyan 1992) [9]. The abundant water environment in which rice grows best differentiates it from all other important crops. But water is becoming increasingly scarce.Per capita availability of water resources declined by 40–60% in many Asian countries between 1955 and 1990 (Gleick 1993) [22]. In 2025, per capita available water resources in these countries are expected to decline by 15–54% compared with 1990. For most of contemporary history, the world’s irrigated area has grown faster than the population. Since 1980, irrigated area per person has declined and per capita cereal grain production has stagnated. Agriculture’s share of water will decline at an even faster rate because of increasing competition for available water from urban and industrial sectors (Tuong and Bhuiyan 1997) [40].

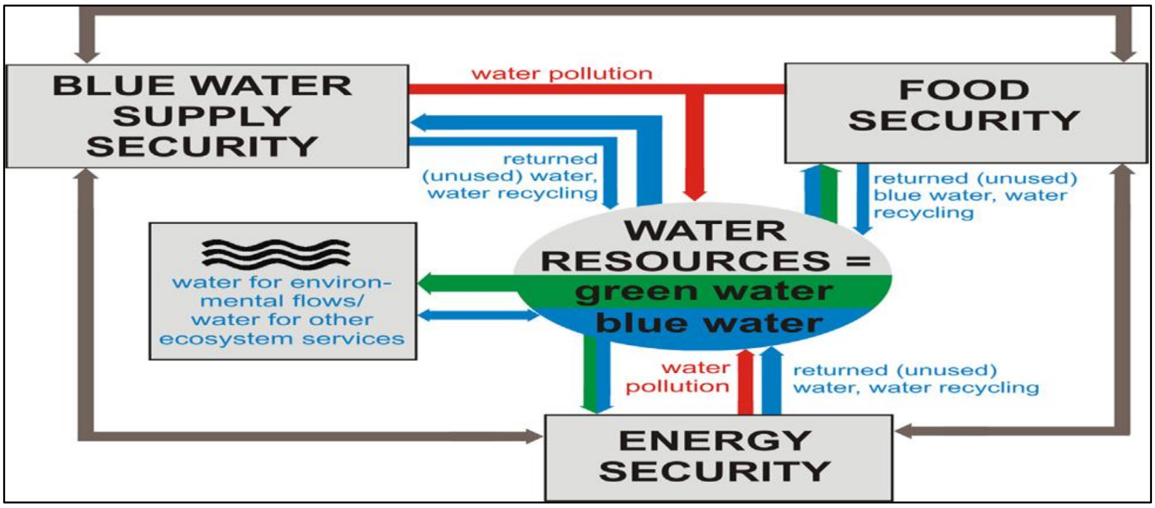


Fig 1: Graphical representation showing (1) available water resources (green and blue) and (2) food security; energy security; blue water supply security and water for environmental flows/water for other eco-system services. (Hoff, 2011)

Brouwer and Heibloem (1986) [11] also suggested that for rice cultivation in wetland systems, paddy fields are prepared and the soil is kept saturated. The common practice is to first prepare land by puddling. This is done by saturating the soil layer for one month prior to sowing. The volume of water (SAT) necessary for this stage is assumed to be 200 mm. As lowland rice is grown in a standing layer of water, there is a constant percolation and seepage loss during this period. Percolation loss (PERC) is primarily a function of soil texture. It varies from 2 mm/day (heavy clay) to 6 mm/day for sandy soil. As rice is mostly grown in soil with more clayey texture, for the present study we have taken 2.5 mm/day as an average (Brouwer and Heibloem, 1986) [11] for the entire period of rice cultivation except for the last 15 days when the field is left to dry out for easy harvesting. A water layer is established during transplanting or sowing and maintained throughout the growing season. Although the volume of water needed for maintaining the water layer (WL) is available for percolation losses and to meet the evaporative demand of the crop during the last phase of paddy growth, it is necessary to get this volume of water at the beginning of the crop period (Figure 2). In this study, it is assumed that a water layer of 100 mm is established in the month of sowing. A time step of five days is chosen for the calculation. The total water demand (WD) is calculated by adding ETc, WL, SAT and PERC for each time step.

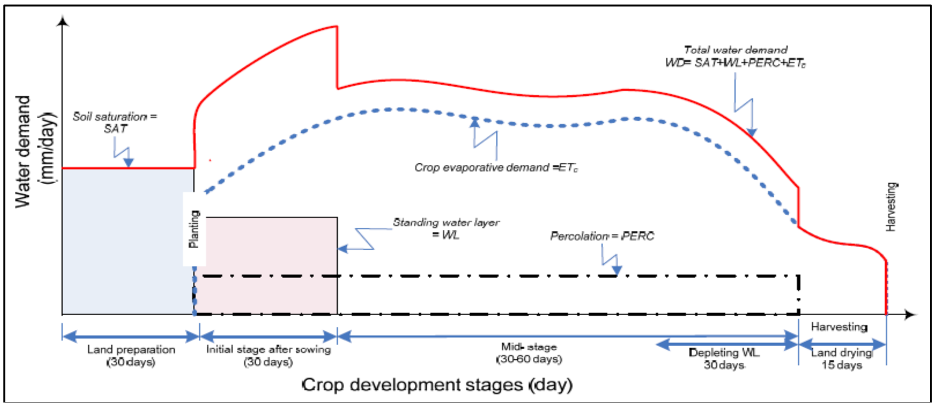


Fig 2: The schema used to estimate the water demand at different stages of rice crop growth.

The spatial and temporal variability in freshwater availability is large in Asia. Regional weather phenomena such as the monsoons and inadequate monitoring make it difficult to predict precipitation locally and to determine the potential impacts of climate change. Water-related natural disasters are a frequent cause of death and destruction in this region. The burgeoning populations in urban and rural areas demand increasingly more water – either directly for their consumption and livelihoods or as water required making the products they consume. All this has placed increasing stress on surface and ground water resources to meet the rising irrigation (that still accounts for 85% of the water consumed in South and East Asia), domestic, industrial, hydropower, community and increasingly important environmental needs. Most river basins are now at the edge of being developed to their maximum capacity. The risks are that basins retain all rainfall water resources in small and large reservoirs, and that the outflow diminishes to virtually nothing (‘closed basin’). This is far from being adequate for maintaining wetlands, estuaries, lagoons and other biodiversity-rich ecosystems that are traditionally found in the lower ends of basins. It has been estimated that during the 20th century, more than 50% of the wetlands are lost (Bos & Bergkamp, 2001) [10].

Remote sensing, when used conjunctively with tools such as geographic information systems (GIS) can be of significant use in improving the productivity of water use through sustainable management of the resource base as well as in effective service delivery (Figure 3). These “eyes in the sky” provide a reliable, useful, unbiased and increasingly inexpensive method to monitor the resource base and use.The new approaches to ascertain soil moisture and ET parameters from remote sensing over large regions helps break away from the vagaries and expenses of field-based measurements alone. This is especially true in Asia, where the water problems are huge, but also where the potential exists to leapfrog traditional management tools and move to modern tools such as satellite remote sensing use that are more appropriate in cost, speed and reliability perspective and that can make use of the skilled manpower base that exists or could be quickly trained. Bastiaanssen and Ali, (2003) [8] revealed that the crop water productivity was investigated in northwest India on the basis of a remote sensing methodology that computes crop yield in a quasi-independent manner. Bastiaanssen *et al*., 2002 [7] found that a remote sensing analysis across the Indo-Gangetic plain with SEBAL was appraising the full spectrum of crop water productivity. This important conclusion implies that increased water productivity can only be achieved by increasing crop yield, thus agronomic inputs are necessary to harvest more “crop per drop.”

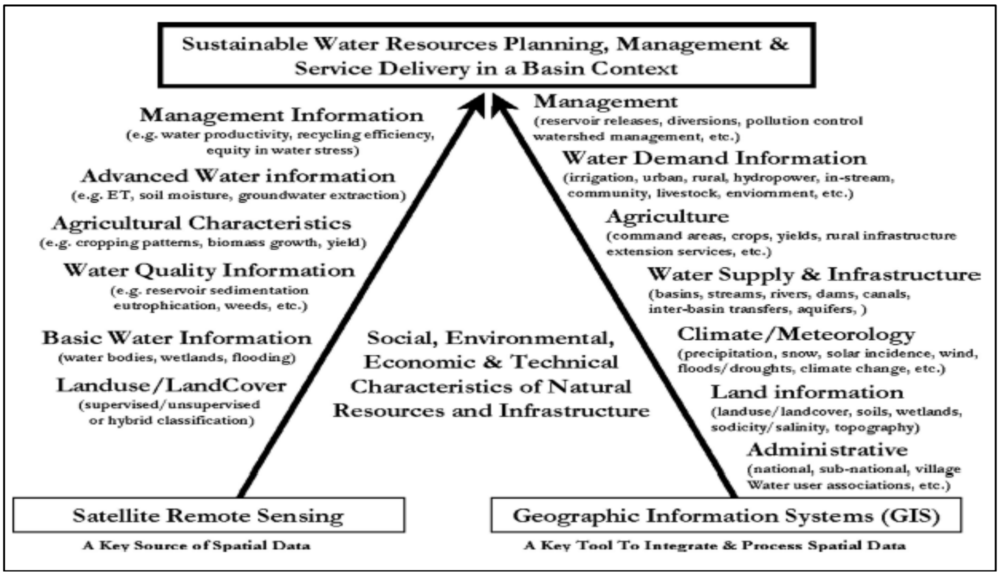


Fig 3: Satellite remote sensing and GIS for better water management.

Chapagain and Hoekstra, 2010 also found that the water use in the rice fields is calculated for each 5-day cumulative period if the total water demand *WD* is less than total water available *WA*, green water use is equal to the demand *WD*. In cases where the *WD* exceeds *WA*, the deficit is to be met by irrigation water supply. This deficit is called irrigation water demand. If a paddy field is 100% irrigated, it is assumed that the 'blue water' use in crop production is equal to the deficit. For areas equipped with partial irrigation coverage, the blue water use is estimated on a pro-rata basis (Figure 4).

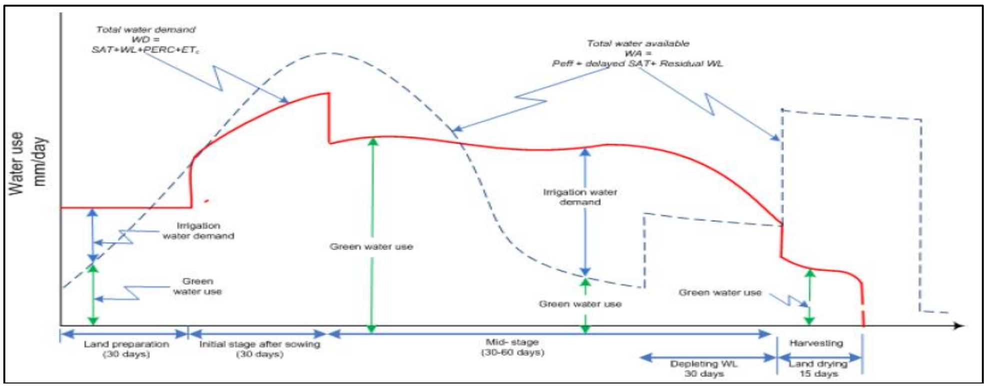
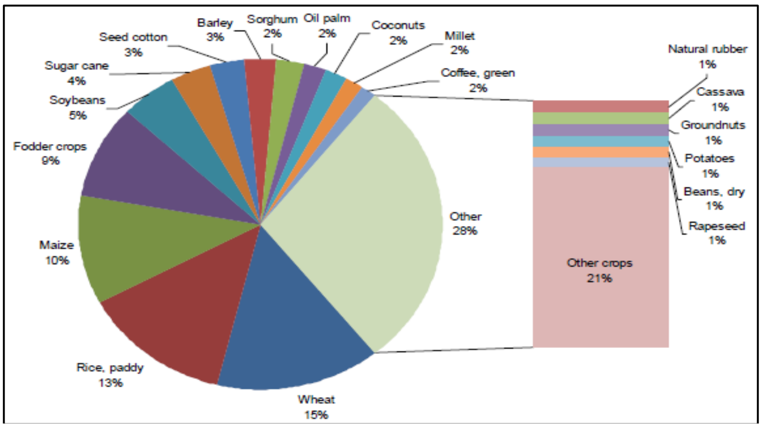


Fig 4: Distinguishing the green water use and irrigation water demand of rice crop.

The water footprint of primary crops

Mekonnen and Hoekstra (2011) [35] revealed that the average water footprint for cereal crops is 1644m^3 ton^{-1}, but the footprint for wheat is relatively large (1827m^3 ton^{-1}), while for maize it is relatively small (1222m^3 ton^{-1}). The average water footprint of rice is close to the average for all cereals together. Sugar obtained from sugar beet has a smaller water footprint than sugar from sugar cane. Besides, the blue component in the total water footprint of beet sugar (20%) is smaller than for cane sugar (27%) and for vegetable oils we find a large variation in water footprints: maize oil 2600m^3 ton^{-1}; cotton-seed oil 3800m^3 ton^{-1}; soybean oil 4200m^3 ton^{-1}; rapeseed oil 4300m^3 ton^{-1}; palm oil 5000m^3 ton^{-1}; sunflower oil 6800m^3 ton^{-1}; groundnut oil 7500m^3 ton^{-1}; linseed oil 9400m^3 ton^{-1}; olive oil 14500m^3 ton^{-1}; castor oil 24700m^3 ton^{-1} (Figure 5).The estimate of the total water footprint related to crop production by Fader *et al*. (2011) [19] is only 4% higher than Mekonnen and Hoekstra estimate. The differences in the outcomes can be due to a variety of causes, including: type of model, spatial resolution, and period considered and data regarding cultivated and irrigated areas, growing periods, crop parameters, soil and climate. Liu and Yang (2010) [33] reported that the estimate of the total water footprint is 11% lower than Mekonnen and Hoekstra estimate. Siebert and Doll (2010) [39] observed that the green water footprint is 4.6% lower than in the Mekonnen and Hoekstra study, while their blue water footprint estimate is 31% higher.



Source: Mekonnen and Hoekstra (2011)

Fig 5: Contribution of different crops to the total water footprint of crop production.

Water footprint related to rice consumption in a country

The water footprint of national consumption can be classified into an internal and an external component. The internal water footprint of rice consumption refers to the consumption and pollution of national water resources to domestically produce rice for own consumption. The external water footprint of rice consumption refers to water used in the countries from where rice is imported for national consumption. The internal and external water footprints are assessed following the scheme shown in Figure 6. Chapagain and Hoekstra 2010 reported that the global average water footprint of paddy rice was 1325 m^3 ton^{-1} (48% green, 44% blue, and 8% grey), which is much lower than previous estimates. There is about 1025 m^3 ton^{-1} of percolation in rice production. The global water footprint of rice production is estimated to be 784 billion m^{3}yr^{-1}.The ratio of green to blue water varies greatly, both over time and space. In countries like India, Indonesia, Thailand, Myanmar and the Phillippines, the green water fraction is substantially larger than the blue water fraction. In the USA, however, the blue water fraction is 3.7 times the green water fraction; in Pakistan 5.6 times.

Alcamo *et al*., (2007) [2] revealed that the largest green water footprint was calculated for the Mississippi river basin (424Gm^3 yr^{-1}) but largest blue water footprints were found in the basins of the Indus (117Gm^3 yr^{-1}) and Ganges (108Gm^3 yr^{-1}).These two river basins together account for 25% of the global blue water footprint. At state level, the largest green water footprints can be found in Uttar Pradesh (88Gm^3 yr^{-1}), Maharashtra (86Gm^3 yr^{-1}), Karnataka (65Gm^3 yr^{-1}), Andhra Pradesh (61Gm^3 yr^{-1}), and Madhya Pradesh (60Gm^3 yr^{-1}), [Chukalla *et al.*, 2015] and the largest blue water footprints were found in: Uttar Pradesh (59Gm^3 yr^{-1}) and Madhya Pradesh (24Gm^3 yr^{-1}), respectively. 1 cup of coffee needs 140 liters of water;

1 liter of milk needs 1000 liters of water;1 kg of wheat needs 1350 liters of water;1 kg of rice needs 3000 liters of water and1 kg maize needs 900 liters of water.

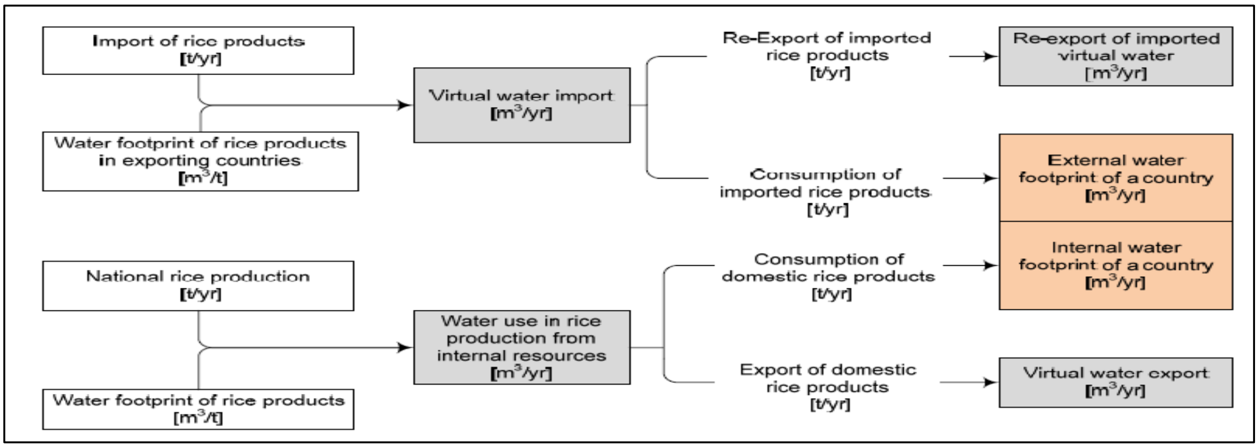
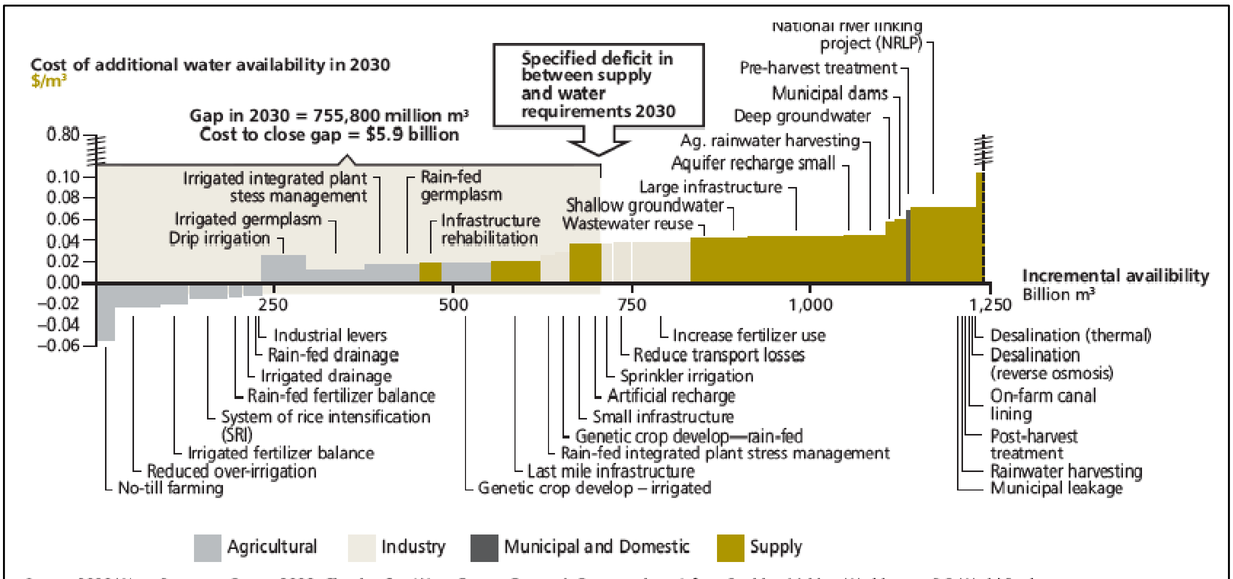


Fig 6: The calculation scheme for assessing the water footprint of national consumption of rice products.

ADB 2013 analyses of the water–food–energy nexus is the water availability cost curve of India (Figure 7).In this form, the cost curve is a purely quantitative measure. However, if well researched and reasonably accurate, its value lies in displaying the range of measures, together with their respective financial costs, that are available to society and the economy to respond to the threat of future water scarcity. An example of the importance of assessing the political economy is that of attempts to improve productivity on small farms throughout Asia. There are enormous water savings to be made by reducing the waste in irrigation water and in the produce that spoils before reaching markets. Yet reaching those millions of small individual farmers will involve convincing a cautious, traditional group of the population. Chapagain and Hoekstra (2011) [14], revealed that rice production in India total water foot print was of 2020 m^3 t^{-1} and percolation volume of 1403 m^{3}t^{-1}, respectively, while rice water footprint was higher in Pakistan (2874 m^3 t^{-1}).

Mekonnen and Hoekstra (2011) [35] reported that total water footprint was for wheat (1087Gm^3 yr^{-1}), rice (992Gm^3 yr^{-1}) and maize (770Gm^3 yr^{-1}). Wheat and rice have the largest blue water footprints, together accounting for 45% of the global blue water footprint. At country level, the total water footprint was largest for India (1047Gm^3 yr^{-1}), China (967Gm^3 yr^{-1}) and the USA (826Gm^3 yr^{-1}). A relatively large total blue water footprint as a result of crop production was observed in the Indus river basin (117Gm^3 yr^{-1}) and the Ganges river basin (108Gm^3 yr^{-1}). They also elaborate that the grey water footprint related to the use of nitrogen fertilizer in crops cultivation was 733Gm^3 yr^{-1}. Wheat (123Gm^3 yr^{-1}), maize (122Gm^3 yr^{-1}) and rice (111Gm^3 yr^{-1}) have large grey water footprint together accounting for about 56% of the global grey water footprint. Mekonnen and Hoekstra (2011) [35] also found that the global water foot print of rice of was 1674 m^3 t^{-1},where 'green', 'blue' and 'grey' WFPs components wee 1488,443 and 242 m^{3}t^{-1}, respectively.



Source: 2030 Water Resources Group. 2009. *Charting Our Water Future: Economic Frameworks to Inform Decision-Making*. Washington, DC: World Bank.

Fig 7: Water Availability Cost Curve-India

Green and blue water resources

Figure 8 presents indicative annual values for current global water resources and water use, as obtained from different literature sources. Each indicated value is obtained from one corresponding single source only. As such, the balance between water resources and water use does not hold100% within the figure. It is shown where WF_{prod} and WF_{cons} values fit within the water flows. Terrestrial precipitation amounts to111, 000km^{3}yr^{-1} (Oki and Kanae, 2006) [36]. This precipitation results in 40–45% blue water resources and 55–60% green water resources. Total blue water resources (51,000km^{3}yr^{-1}) include ground water (GW) (15,000km^{3}yr^{-1}) and surface water (SW) (36,000km^{3}yr^{-1}) (Wada etal.,2010). The value for total blue water resources is within the range from 42,000 to 66,000km^{3}yr^{-1}. The value for total green water resources (65,000km^3 yr^{-1}) is within the range from 60,000 to 85,000 as reported by (Haddeland *et al*. 2011) [23]. According to (Gerten etal. 2013), ecological available blue water (surface and groundwater), or PB-blue water, is within the range1100–4500km^{3}yr^{-1}. (Pastor *et al*., 2013) [37] describe highest environmental flow requirements to be at 48% of mean annual flows and lowest environmental flow requirements at 26% of mean annual flows.

Water use for municipalities

According to (Döll *et al*. 2012) [18], total water abstraction for domestic purposes is 330km^{3}yr^{-1} (36%GW, 64%SW), of which 53km^{3}yr^{-1} is consumptive use. Although often defined as domestic water, these volumes actually represent municipal water use. Municipal water use (or public water use) includes domestic water use and commercial water use (Vanham and Bidoglio, 2014) [41]. The latter includes water supply to small businesses, hotels, offices, hospitals and schools. Public water use also represents water for non-permanent residents (like commuters or tourists). It can also include a part of industrial water use which is connected to the municipal network. In WF assessments, this municipal use is referred to as the WF of domestic water use. The WF_{prod} equals the WF_{cons}. The blue component amount is 42km^{3}yr^{-1} (Hoekstra and Mekonnen, 2012) [28]. For its calculation a consumptive portion of 10% of abstracted water was used (Hoekstra and Mekonnen, 2012) [28]. In this paper this component will be referred to as the municipal WF ($WF_{prod, mun}$ and $WF_{cons, mun}$).

Water use for food security

The agricultural WF_{prod} (or $WF_{prod, agr}$) consists of green (5771km^{3}yr^{-1}) and blue (899km^{3}yr^{-1}) (and gray, 733km^{3}yr^{-1}) water for crop production, green grazing water (913km^{3}yr^{-1}) and blue drinking and service water (46km^{3}yr^{-1}) for livestock (Hoekstra, 2014). The green and blue values for $WF_{prod, agr}$ result from the spatially distributed modeling of 126 (edible and some non-edible) crops. The crop irrigation blue water consumption (899km^{3}yr^{-1}) is in the lower range of global estimates, buttotal crop consumption (gnþbl 6670km^{3}yr^{-1}) is rather average amongst other global estimates (Mekonnen and Hoekstra, 2011) [27]. The $WF_{prod, agr}$ for livestock (grazing and service water, feed crops are included in the crops $WF_{prod, agr}$) were computed for 8 farm animal categories (Mekonnen and Hoekstra, 2012a) [34].

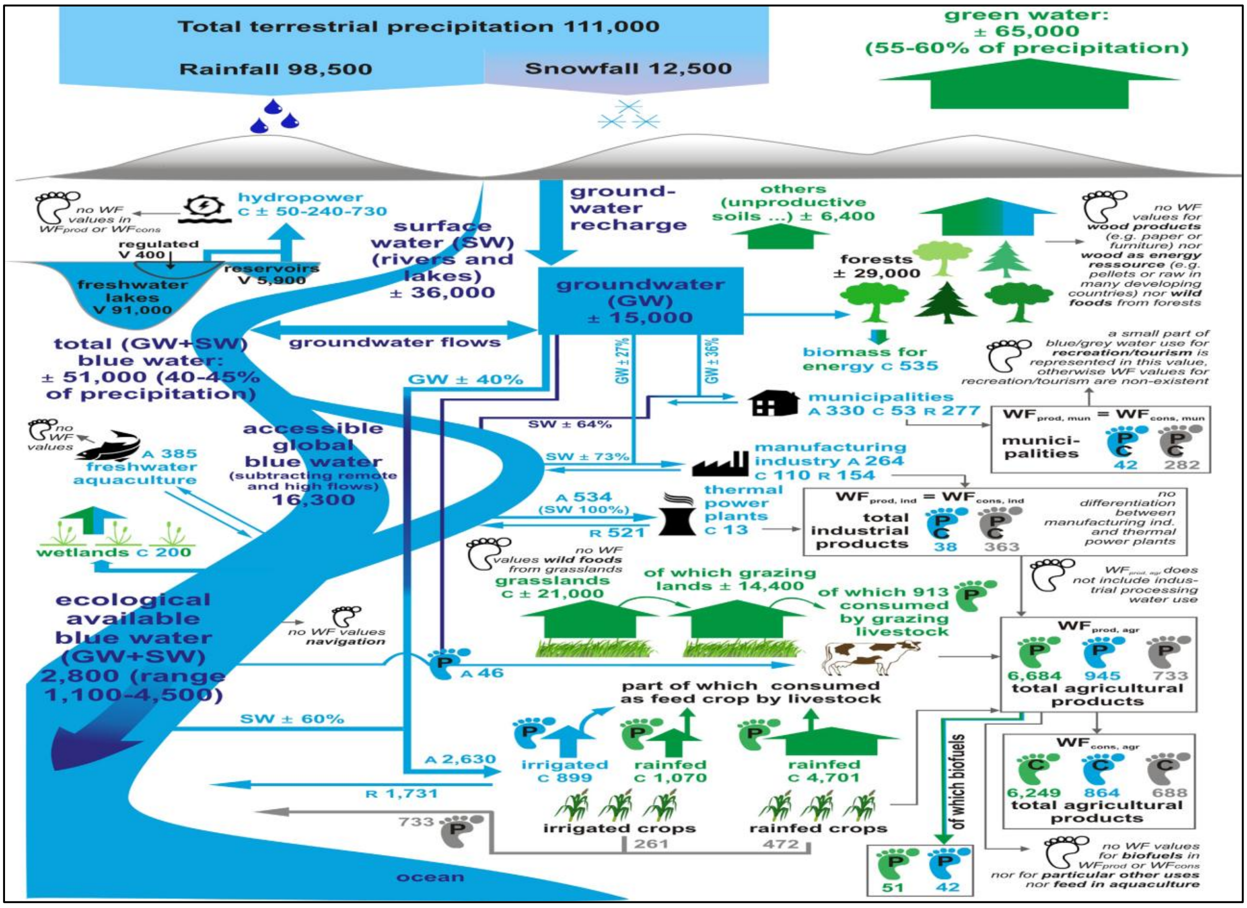


Fig 8: Indicative values for current global water resources (fluxes) and water use. Water volume values are in km^3/yr. Green arrows relate to green water, blue arrows to blue water, gray arrows to gray water. Abbreviations: A=Abstraction; C=Consumption; R=Return flow (to both surface and groundwater); SW=Surface water; GW=Groundwater; V=Volume or storage; P within footprint sign=WF_{prod}; C within footprint sign= WF_{cons}; mun=municipalities; ind= industries; agr=agriculture. Data sources are listed in the text.

Conclusion

The large fraction of green water (78%) confirms the importance of green water in food production. The fraction of blue water is smaller (12%), but as the spatial analysis shows, the regions where blue water footprints are large are often arid and semi-arid regions where water scarcity is high. The share of the grey water footprint is relatively small as well (10%), but this is a conservative estimate, because we have analyzed the required assimilation volume for leached nitrogen fertilizers only, leaving out relevant pollutants such as phosphorus and pesticides. Green water plays a prominent role in the rice production and there is great opportunity to improve water productivity through improving yield levels within the available water balance in subtropical agriculture. This offers a good opportunity to increase food production from subtropical agriculture by raising water productivity without requiring additional blue water resources. Better use of rain wherever possible, that means increasing yields per drop of rainwater, will reduce the demand for rice from areas where blue water is a necessary input. From an economic point of view, reducing percolation of blue water in the rice fields is relevant, because it will reduce costs of water supply. The environmental benefit is not so big, because percolated blue water will remain within the same catchment as from where it was abstracted. As a lot of water is percolating in the first phase of the land preparation, a number of water saving technologies have been adopted which can be a favorable option where the supply is limited or scarce.

Globally, there is nearly an equal share of green and blue water use in the total water footprint of rice. The green water footprint (rain) has a relatively low opportunity cost compared to the blue water footprint (irrigation water evaporated from the field). The environmental impact of the blue water footprint in rice production depends on the timing and location of the water use. It would need a dedicated analysis to estimate where and when blue water footprints in rice production constitute significant environmental problems, but from our critical review it is obvious that rice from the subtropical India, where rice production heavily depends on blue water, will generally cause larger impacts per unit of product. Therefore, a carefully balanced green-blue water use strategy would be required to address the issue of increasing water demand in a world of limited freshwater resources. For further research it is important to assess the spatiotemporal variability of blue water availability and how much blue water can sustainably be used in a certain catchment without adversely affecting the ecosystem. Current assessment relies overwhelmingly on statistical data, which are variable in quality, the spatial scale is often poor and does not correspondent to hydrological boundaries. Remote sensing is a powerful tool to estimate both crop production and consumptive water use. Basin-scale hydrological modeling also helps to study the processes of water cycling and to examine existing interventions. Combining the two provides greater opportunities to capture images of WP as well as understanding processes on the ground.

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