Agricultural Water Footprint Studies for sustainable agricultural water management : A review

Abstract:

Water footprint is defined as the amount of water consumed in production of any agricultural or industrial produce. It accounts the water consumed directly and indirectly for producing any industrial and agricultural product. Water footprint analysis helps in planning of the optimum utilization of water in any sector which subsequently leads to sustainable management of water resources. This review paper provides a review on the Water Footprint estimation methodology its merit and shortcomings, practical challenges with available data and resources for Indian context and worldwide. With increasing population and industrialization, availability of water and its judicious distribution is becoming challenging for the policy makers and strategist. Water foot print mapping of major crops will be helpful for development of new varieties which will be having higher yield with less water consumption. Traditional water consumption statistics, policies and awareness drives focuses on reducing water wastage and improving water use efficiency in domestic and industrial water use. Water footprint studies for various regions of India find that climate change and agricultural practices has significantly reduced the water consumption.

Keywords: Water Footprint, Blue Water, Green Water, Grey Water.

1. Introduction

The origin of the water footprint stems from the concept of “virtual water” coined by Allan (1997) when studying the option of importing virtual water (as opposed to real water) as a partial solution to problems of water scarcity in the Middle East. Allan noticed that “rather than importing huge quantities of water to achieve food self-sufficiency, a significant number of water scarce countries in the Middle East were importing grains instead. The inverse of the virtual water content is known as the water productivity of a crop”. He elaborated on the idea of using virtual water import (coming along with food imports) as a tool to release the pressure on the scarcely available domestic water resources.

1.1. Virtual Water

Virtual water is the volume of water required to grow, produce and package agricultural commodities and consumer goods. The term “virtual” was preferred as the final product usually contains only a small fraction of water compared to the total volume of water actually used for its production. “Virtual water is also referred to as embedded water or hidden water. Virtual water is defined as the volume of water required to produce a commodity or service measured at the place where the commodity is actually produced” (Allan, 1993, 1994).

1.2. Water Footprint

Building upon the concept of virtual water, Hoekstra and Hung (2002) sought “to quantify these virtual water flows related to international food trade and thus developed the water footprint concept. From a production perspective, the water footprint is numerically equal to the virtual water content of a given product or service; what distinguishes the water footprint from virtual water is that it is also applied at a consumer level, thus creating a consumption based indicator of water use”. “The water footprint concept was introduced to have a consumption based indicator of water use that could provide useful information in addition to the traditional production-sector-based indicators of water use” (Hoekstra and Hung, 2002).

“The water footprint has been developed in analogy to the ecological footprint concept as was introduced in the 1990s” (Rees, 1992; Wackernagel and Rees, 1996; Wackernagel et al., 1997). “The ecological footprint of a population represents the area of productive land and aquatic ecosystems required to produce the resources used, and to assimilate the wastes produced, by a certain population at a specified material standard of living, wherever on earth that land may be located. Whereas the ecological footprint thus quantifies the area needed to sustain people’s living, the water footprint indicates the water required to sustain a population”.

The water footprint of a product is an empirical indicator of how much water is consumed and polluted, when and where, measured over the whole supply chain of the product. The water footprint is a multidimensional indicator, showing volumes but also making explicit the type of water use (consumptive use of rainwater, surface water or groundwater, or pollution of water) and the location and timing of water use. The water footprint of an individual, community or business, is defined as the total volume of freshwater that is used to produce the goods and services consumed by the individual or community or produced by the business. The water footprint shows human appropriation of the world’s limited freshwater resources and thus provides a basis for discussing water allocation and issues that relate to sustainable, equitable and efficient water use. Besides, the water footprint forms a basis for assessing the impacts of goods and services at catchment level and formulating strategies to reduce those impacts.

Traditionally water use focus on measuring water withdrawals and direct water use. The water footprint accounting method takes a much broader perspective. First of all, the water footprint measures both direct and indirect water use, where the latter refers to the water use in the supply chain of a product. The water footprint thus links final consumers and intermediate businesses and traders to the water use along the whole production chain of a product. This is relevant, because generally the direct water use of a consumer is small if compared to its indirect water use and the operational water use of a business is generally small if compared to the supply chain water use. So the actual water dependency of a consumer and business can change. The water footprint method differs further in that it looks at water consumption (as opposed to withdrawal), where consumption refers to the part of the water withdrawal that evaporates or gets incorporated into a product. Besides, the water footprint goes beyond looking at blue water use only (use of ground and surface water). It also includes a green water footprint component (use of rainwater) and a grey water footprint component (polluted water).

1.3. Water Footprint expression

"A water footprint is expressed in terms of a water volume per unit of product or as a water volume per unit of time. The water footprint of a process is expressed as water volume per unit of time. When divided over the quantity of product that results from the process, it can also be expressed as water volume per unit product. A product water footprint is always expressed in terms of water volume per unit of product (m^3/ton or litre/kg). The water footprint of a consumer or producer or the water footprint within an area is always expressed as water volume per unit of time. Depending on the level of detail that one aims to provide, the water footprint can be expressed per day, month or year. In general, it can be expressed as water volume per unit of mass (for products where weight is a good indicator of quantity) or water volume per unit of money (for products where value tells more than weight) or water volume per piece (for products that are counted per piece rather than weight) or water volume per unit of energy (per kcal for food products, or per Joule for electricity or fuels). It can be expressed as water volume per monetary unit when the water footprint per unit of time is divided by income (for consumers) or turnover (for businesses). The water footprint of a community of consumers can be expressed in terms of water volume per unit of time per capita. The water footprint within a geographically delineated area is expressed as water volume per unit of time. It can be expressed in terms of water volume per monetary unit when divided over the income in the area". [42]

2. Components of water footprint

The water footprint is an indicator of freshwater use that looks at both direct and indirect water use of a product, services, consumer or producer along supply chain. The water footprint can be regarded as a comprehensive indicator of freshwater resources appropriation, next to the traditional and restricted measure of water withdrawal. The water footprint of a product is the volume of freshwater used to produce the product measured over the full supply chain. It shows water consumption volumes by source and polluted volumes by pollutants. All the components of a total water footprint are specified geographically and temporally. It has three components green, blue and grey.

2.1 The blue water footprint: It refers to consumption or loss of blue water resources i.e. surface and groundwater along the supply chain of a product. Losses occur when water evaporates, returns to another catchment area or the sea is incorporated into a product.

2.2 The green water footprint: It refers to consumption of green water resources i.e. rainwater insofar as it does not become run-off.

2.3 The grey water footprint: It refers to pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants given natural background concentrations and existing ambient water quality standards.

"One part of the precipitation above land evaporates and the other part runs off to the ocean through aquifers and rivers. Both the evaporative flow and the runoff flow can be made productive for human purposes. The evaporative flow can be used for crop growth or left for maintaining natural ecosystems; the green water footprint measures what part of the total evaporative flow is actually appropriated for human purposes. The run-off flow – the water flowing in aquifers and rivers – can be used for all sorts of purposes, including irrigation, washing, processing and cooling. The blue water footprint measures the volume of groundwater and surface water consumed (in other words, withdrawn and then evaporated or incorporated into a product). The grey water footprint measures the volume of water flow in aquifers and rivers polluted by humans. In this way, the green, blue and grey water footprint measure different sorts of water appropriation". [42]

Freshwater is vital for life. It is a scarce resource with limited annual availability and growing demand. The water footprint of humanity has exceeded sustainable levels in several places and is unequally distributed among people. Good information regarding water footprints of communities and businesses will help us to understand how we can achieve a more sustainable and equitable use of freshwater. There are many spots in the world where serious water depletion or pollution takes place: rivers running dry, dropping lake and groundwater levels and endangered species resulting from contaminated water. The water footprint helps to show the link that exists between our daily consumption of goods and the problems of water depletion and pollution that exist elsewhere, in the regions where our goods are produced. Nearly every product has a smaller or larger water footprint, which is of interest for both the consumers that buy those products and the businesses that produce, process, trade or sell those products in some stage of their supply chain.

3. Green, blue and grey water footprint of crop

Crops are used for food, feed, fibre, fuel, oils, soaps, cosmetics and so on. Wood from trees and shrubs is used for timber, paper and fuel. Since the agricultural and forestry sectors are major water-consuming sectors, products that involve agriculture or forestry in their production system will have a significant water footprint. For all those products it is relevant to particularly look into the water footprint of the process of growing the crop.

The total water footprint of the process of growing crops (WFproc) is the sum of the green, blue and grey components:

WF proc= WF proc, green + WF proc, blue + WF proc, grey (volume/mass)

WF proc, green = CWU green/ Y (volume/mass)

WF proc, blue = CWU blue / Y (volume/mass)

Where CWU= crop water use in m3/ ha

The crop water requirement is calculated using reference crop evapotranspiration (ETo) and the crop coefficient (Kc) as below:

ETc = Kc × ETo.

ETc = CWR

If crop water requirements are fully met, so that actual crop evapotranspiration (ETc) will be equal to the crop water requirement.

Green water evapotranspiration (ETgreen), evapotranspiration of rainfall, can be equated with the minimum of total crop evapotranspiration (ETc) and effective rainfall (Peff). Blue water evapotranspiration (ETblue), field-evapotranspiration of irrigation water, is equal to the total crop evapotranspiration minus effective rainfall (Peff), but zero when effective rainfall exceeds crop evapotranspiration:

ETgreen = min (ETc , Peff) (length/time)

ETblue = max (0, ETc – Peff) (length/time)

All water flows are expressed in mm per day or in mm per period.

4. Water Footprint Studies at International level

Several researchers have studied and analysed water footprint of different commodities and countries worldwide. "Study on virtual water flows between nations during 1995–1999 related to international crop trade and national virtual water balances in relation to national water needs and water availability was carried out" by Hoekstra and Hung (2005). The calculations based on multiply international crop trade flows by their associated virtual water content show that the global volume of crop-related international virtual water flows between nations was 695 Gm3 annually. The total water use by crops in the world was estimated at 5400 Gm3. It indicates that 13% of the water used for crop production was not used for domestic consumption but for export in the form of virtual water. The countries with the largest net virtual water export are United States, Canada, Thailand, Argentina and India. The largest net import appears to be Japan, the Netherlands, the Republic of Korea, China and Indonesia.

Hoekstra and Chapgain (2007) assessed "the water footprint for each nation of the world for the period 1997–2001. They found that USA appears to have an average water footprint of 2480 m3/cap/yr, while China has an average footprint of 700 m3/cap/yr. The global average water footprint is 1240 m3/cap/yr. The four major direct factors determining the water footprint of a country are: volume of consumption (related to the gross national income); consumption pattern (e.g. high versus low meat consumption); climate (growth conditions); and agricultural practice (water use efficiency)". The aggregated external water footprints of nations in the world constitute 16% of the total global water footprint. However, the share of the external water footprint varies from country to country. Some African countries, such as Sudan, Mali, Nigeria, Ethiopia, Malawi and Chad have hardly any external water footprint, simply because they have little import. Some European countries on the other hand, e.g. Italy, Germany, the UK and the Netherlands have external water footprints contributing 50–80% to the total water footprint. The agricultural products that contribute most to the external water footprints of nations are: bovine meat, soybean, wheat, cocoa, rice, cotton and maize. Eight countries – India, China, the USA, the Russian Federation, Indonesia, Nigeria, Brazil and Pakistan – together contribute fifty percent to the total global water footprint. India (13%), China (12%) and the USA (9%) are the largest consumers of the global water resources. China, India, and the United States are the countries with the largest total WF within their territory, with total WF of 1,207; 1,182; and 1,053 Gm3/y, respectively. About 38% of the WF of global production lies within these three countries. Water foot print of some crops and virtual water content of some products is depicted in Table 1 and 2.

Table 1: Water footprint of crops

Crops	WFP, m 3/t
Wheat	1827
Cereal	1744
Maize	1222
Fruits	1000
Water melon	235
Pineapple	255
Papaya	460
Orange	560
Banana	790
Apple	820
Cabbage	230
Tomato	214
Cauliflower	285
Egg plant	363
Chillies	379
Pea	595
Okra	579

Table 2: Virtual water content of some products

Product	Virtual water content (litres)
1 pair of shoes (bovine leather)	8000
1 hamburger (150 g)	2400
1 cotton T-shirt (250 g)	2000
1 glass of milk (200 ml)	200
1 glass of apple juice (200 ml)	190
1 bag of potato crisps (200 g)	185
1 glass of orange juice (200 ml)	170
1 cup of coffee (125 ml)	140
1 egg (40 g)	135
1 glass of wine (125 ml)	120
1 slice of bread (30 g) with cheese(10 g)	90
1 glass of beer (250 ml)	75
1 apple (100 g)	70
1 orange (100 g)	50
1 slice of bread (30 g)	40
1 cup of tea (250 ml)	35
1 microchip (2 g)	32
1 potato (100 g)	25
1 tomato (70 g)	13
1 sheet of A4-paper (80 g/m2)	10
Source: A. Y. Hoekstra · A. K. Chapagain, 2007	

Hoekstra and Chapagain (2008) have shown that “visualizing the hidden water use behind products can help in understanding the global character of fresh water and in quantifying the effects of consumption and trade on water resources use. The improved understanding can form a basis for a better management of the freshwater resources”. The water footprint thus offers a better and wider perspective on how a consumer or producer relates to the use of freshwater systems. Water footprint accounts give spatiotemporally explicit information regarding how water is appropriated for various human purposes through consumption and pollution. Water footprint assessment refers to the activities to (i) quantify and locate the water footprint of a process, product, producer or consumer or to quantify in space and time the water footprint in a specified geographic area; (ii) assess the environmental, social and economic sustainability of this water footprint; and (iii) formulate a response strategy. The goal of assessing water footprints is to analyze how human activities or specific products relate to issues of water scarcity and pollution, and to see how activities and products can become more sustainable from a water perspective. When a product includes ingredients that originate from agriculture, those ingredients often give a major contribution to the overall water footprint of the product because an estimated 86% of the water footprint of humanity is within the agricultural sector.

"Detailed national WF studies have been conducted for European countries" by Aldaya et al. (2008) for Spain, Sonnenberg et al. (2009) for Germany, Van Oel et al. (2009) for Netherlands, and Vanham (2013) for Austria. Bulsink et al. (2010) studied water footprint for Indonesia, Liu and Savenije (2008) for China, and Verma et al. (2009) for India. "These studies include blue and green water. The green water is the soil water held in the unsaturated zone, formed by precipitation and available to plants, while blue water refers to liquid water in rivers, lakes, wetlands and aquifers. Irrigated agriculture receives blue water (from irrigation) as well as green water (from precipitation), while rainfed agriculture only receives green water" Rockstrom et al. (2009). "Traditional water use statistics only account for blue water. Conventional approaches to water management have focused on managing solely the blue component of the water cycle. However, green water component in water management studies should be included" (Falkenmark, 2003; Falkenmark and Lannerstad, 2007; Vanham, 2012). "Rainfed agriculture is the largest green water user and irrigated agriculture is the largest blue water user worldwide. Many studies now include the green component of the water cycle in water management studies" (Glavan et al., 2012 and Willaarts et al., 2012).

"Water withdrawals for agriculture account for 71 km3, of which 30 km3 are consumed by irrigation and 6 km3 by livestock. The largest blue water consumer in the EU is thus irrigation. The crops maize, olives, cotton, rice and grapes account for more than 50% of blue water consumption in the EU. Grazing in the EU accounts for a green water consumption of 55 km3, whereas green crop consumption amounts to 396 km3" (Mekonnen and Hoekstra, 2011). "The latter is more than 10 times the blue water consumption (irrigation) of crop production, i.e. in the EU, green crop consumption accounts for 93% of total crop water consumption and blue water consumption only for 7%. Worldwide these values are 86% and 14%. Crop green water consumption in the EU accounts for 7% of total global crop green water consumption, whereas the EU value for irrigated consumption is 3% of the global value. The most important crops regarding green water consumption in the EU are wheat, fodder crops, barley and maize. Substantial amounts can be accounted to olives, grapes, rapeseed, sunflower, potato, sugar beet and rye". (Mekonnen and Hoekstra, 2011)

"The VWCEU28 for almost all products is considerably lower than the VWCglob. This means that it requires less VW to produce the same amount of product in the EU28 as compared to globally. The value of the VWC is a measure for water efficiency, and is dependent on production methods (yield, method of irrigation, etc.), but also natural conditions (climate and soil). Therefore, it can differ substantially for different regions, even for neighbouring farmers. This means that also within the EU28 important differences exist. Wheat, e.g. has a lower VWC in western Europe and northern Europe as compared to southern Europe or eastern Europe". (Mekonnen and Hoekstra, 2011).

Mekonnen and Hoekstra (2011) quantified "the green, blue and grey water footprint of global crop production for the period 1996–2005. Considering the water footprints of primary crops, we see that the global average water footprint per ton of crop increases from sugar crops (about 200 m3 /ton), vegetables (300 m3 /ton), roots and tubers (400 m3 /ton), fruits (1000 m3/ton), cereals (1600 m3 /ton), oil crops (2400 m3 /ton), pulses (4000 m3 /ton), spices (7000 m3 /ton) to nuts (9000 m3 /ton). The water footprint varies, across different crops per crop category and per production region as well. When considered per ton of product, commodities with relatively large water footprints are: coffee, tea, cocoa, tobacco, spices, nuts, rubber and fibres".

The global water footprint related to crop production in the period 1996–2005 was 7404 billion cubic meters per year (78 % green, 12 % blue, 10 % grey) as quantified by Mekonnen and Hoekstra (2011). A large total annual water footprint was calculated for wheat (1087 Gm3 : 70 % green, 19 % blue, 11 % grey), rice (992 Gm3) and maize (770 Gm3). The global average blue water footprint related to crop production was 899 Gm3. Wheat (204 Gm3) and rice (202 Gm3) have large blue water footprint together 45 % of the global blue water footprint. The global average green water footprint related to crop production was 5771 Gm3, of which rain-fed crops use 4701 Gm3 and irrigated crops use 1070 Gm3. Rain-fed agriculture has a water footprint of 5173 Gm3 (91% green, 9 % grey); irrigated agriculture has a water footprint of 2230 Gm3 (48% green, 40 % blue, 12 % grey). For most of the crops, the contribution of green water footprint toward the total consumptive water footprint (green and blue) is more than 80 %. The grey water footprint related to the use of nitrogen fertilizer in crops cultivation was 733 Gm3 . Wheat (123 Gm3), maize (122 Gm3) and rice (111 Gm3) have large grey water footprint together accounting for about 56 % of the global grey water footprint. The total annual water footprint was largest for India (1047 Gm3), China (967 Gm3) and the USA (826 Gm3), Brazil, Russia and Indonesia. These six countries together account for about half of the global total water footprint related to crop production. The largest green water footprints are also found in these six countries: India, China, the USA, Russia, Brazil and Indonesia. The largest blue water footprints were calculated for India, China, the USA and Pakistan. These four countries together account for 58% of the total blue water footprint related to crop production. At sub-national level, the largest blue water footprints were found in: Uttar Pradesh (59 Gm3) and Madhya Pradesh (24 Gm3) in India; Punjab (50 Gm3) in Pakistan; and California (20 Gm3) in the USA. Large grey water footprints were estimated for China, the USA and India. Global average water footprint of 14 primary crop categories for period: 1996–2005 is presented in Table 3.

Table 3: Global average water footprint of 14 primary crop

Crops	Water Footprint (m^3 /ton)			
	Green	Blue	Grey	Total
Sugar crops	130	52	15	197
Fodder crops	207	27	20	253
Vegetables	194	43	85	322
Roots and tubers	327	16	43	387
Fruits	727	147	93	967
Cereals	1232	228	184	1644
Oil crops	2023	220	121	2364
Tobacco	2021	205	700	2925
Fibres, vegetal origin	3375	163	300	3837
Pulses	3180	141	734	4055
Spices	5872	744	432	7048
Nuts	7016	1367	680	9063
Rubber, gums, waxes	12964	361	422	13748
Stimulants	13731	252	460	14443
Source: Mekonnen and Hoekstra (2011)				

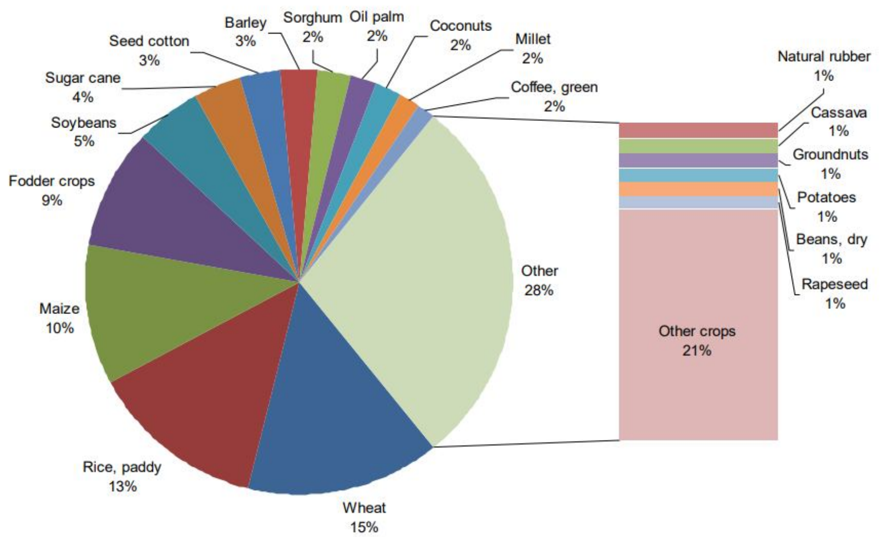

Figure 1: Contribution of different crops to the total water foot print of crop production (source: Mekonnen and Hoekstra, 2011)

The water footprint (WF) and its applicability for EU28 was reviewed by Vanham and Bidoglio (2013) which results in “an EU28 WF of production of 609 km3 /yr and a WF of consumption of

857 km3 /yr. WF of consumption consists of 60% as internal and 40% as external to Europe. The EU28 is a net virtual water importer. The WF of agricultural products contributes by far the largest fraction of the total WF, i.e. 91% of the total WF of production and 89% of the WF of consumption. With traditional water use statistics, awareness campaigns and policy have always focused on increasing water efficiency in domestic and industrial water use. However, much more water can be saved in agricultural production processes, by reducing food waste and by a change in diet of the average EU consumer. Practical complexities with data (availability of and inconsistencies in the underlying databases) are a concern. Some conceptual aspects need to be further developed and tested. The most important limitation is the fact that it is a partial tool to be used in combination with other analytical means or indicators when determining integrated policy options".

"The importance of water footprint is linked to the need of taking consciousness about water content in products and services and of the achievable changes in productions, diets and market trades. In early studies, the main aim of WFP study was to assess products' water trade on a global scale, while in the subsequent years, goal was the rigorous quantification of its three parts for specific crops and in specific geographical areas. In the recent assessments, similarities about the methodology and the employed tools emerged. About 78% of studies on WFP aimed to quantify Water Footprint, while the remaining 22% analysed methodology, uncertainty, future trends and comparisons with other footprints. About 33% studies quantified Water Footprint concerned with cereals, among which maize and wheat were the most investigated ones. In 46% of studies all the three components were assessed., Only blue or green and blue components were quantified in 37% studies. No indication about the subdivision was given; in 18% the studies" (Daniela et al, 2016).

Firda and Purwanto (2018) carried "the study on Water Footprint Assessment in the Agro-industry. They studied that the sustainable use of water resources bring challenges related to the production and consumption phase of water intensive related goods in the agro-industry. The total water footprint from soy sauce production in Grobogan Regency Indonesia was studied which was equal to the sum of the supply chain water footprint and the operational water footprint. The assessment is based on the production chain diagram of soy sauce production which presenting the relevant process stages from the source to the final product. The result of this research is the total water footprint of soy sauce production is 1986.35 L/kg with fraction of green water 78.43%, blue water 21.4% and gray water 0.17%".

Turkey's blue and green WF of wheat production, consumption and virtual water trade between 2008 and 2019 was analyzed by Muratoglu (2020). He found "total annual consumptive WF of wheat production and consumption of Turkey as 39.3 and 48.1 Gm3, respectively. The average blue and green VW contents of wheat production through Turkey are assessed to be 1161 and 748 m3/ton, respectively. The water footprint parameters of each province are calculated and discussed using climatic and agricultural data. VW transfer of Turkey's international wheat trade is also analyzed. Total national water saving is calculated as 7.8 Gm3/year which is mostly imported from Russia. Global VW deficit due to international wheat trade is calculated to be 1.76 Gm3/year”. Muratoglu (2020)..

Makonnen and Gerbens-Leenes (2020) carried “the study on water footprint of global food production and found that agricultural production is the main consumer of water. The estimated global consumptive (green and blue) water footprint ranges from 5938 to 8508 km3/year. The water footprint is projected to increase by 22% due to climate change and land use change by 2090. Approximately 57% of the global blue water footprint is shown to violate the environmental flow requirements. Therefore, to improve the sustainability of water and protect ecosystems needful action may be done towards increasing water productivity, setting benchmarks, setting caps on the water footprint per river basin, shifting the diets to food items with low water requirements, and reducing food waste. The unsustainable footprint is dominated by only six crops, wheat, rice, cotton, sugar cane, fodder, and maize, and are located in only five countries, India, China, the US, Pakistan, and Iran. Population growth and dietary shifts, e.g., larger meat consumption, is expected to increase demand for water. The estimated global WF ranges from 5938 to 8508 km3/year, increasing by 20% - 30% between 2010 and 2050”.

Study on water security analysis using water footprint approach was done in a river basin (Taranto, Italy) under human pressures by D’Ambrosio et. al. (2020). “Considering all the anthropogenic activities in the basin, including agriculture and the treated effluent disposed via wastewater treatment plants, the average annual water footprint was found to be 213.9 Mm3, of which 37.2%, 9.2% and 53.6% comprised respectively for green, blue and grey water footprint. The study revealed that pollution was the main factor affecting surface water security”. (Weersoorya et al, 2021)

“Industrial sector is mostly accused for the increased water pressure with high water consumption rates and increased grey water footprints. Industries must take action toward implementing water conservation strategies to enhance natural water cycle, increase water-use efficiency and address future challenges. The significance of water footprint as a driving force to water conservation is spotlighted with severe water scarcity. Sustainable Development Goals proposed by the United Nations are focused on creating a sustainable way of life to reduce the impacts on ecology and achieve economic and social benefits which are interlinked with sustainable water use as water is a central part in sustainable development. The concept of water footprint should be used to achieve Sustainable Development Goals in relation to industrial water conservation and the future pathways that lead to sustainable water resource management” (Weersoorya et al, 2021).

5. Water Footprint Studies in India

“The population of India is expected to 1640 million by the year 2050. As a result, gross per capita water availability will decline from 1820 m3 / yr in 2001 to as low as 1140 m3 /yr in 2050. Total water requirement of the country for various activities around the year 2050 has been assessed to 1450 km3 /yr. This is significantly more than the current estimate of utilizable water resource potential (1122 km3 /yr) through conventional development strategies. Therefore, when compared with the availability of 500 km3 /yr at present, the water availability around 2050 needs to be almost trebled. Various options have been considered in quantitative terms, as possible sources to augment the anticipated deficit" (Gupta and Deshpande, 2004).

A study on water footprint of India was conducted for the period 1997-2001 by Kampman et al 2008. "It was found that the total virtual water flow as a result of interstate trade in agricultural commodities in India was 106 billion m3 /yr, which was equal to 13% of the total water use in Indian agriculture. In the same period, the net international export from India was 15 billion m3 /yr. Of the total virtual water flow within India, 35% is due to the interstate trade of milled rice, 17% due the interstate trade of raw sugar and 14% due to the interstate trade of edible oils. The largest interregional net virtual water flow is 22 billion m3 /yr and flows from the North India to the East India. As a result of international and interstate virtual water flows, the states Haryana, Madhya Pradesh, Punjab and Uttar Pradesh relatively have the largest negative virtual water balance and Bihar, Jharkhand and Kerala relatively have the largest positive virtual water balance" (Kampman et al, 2008). During study period, the average water footprint of the consumption of agricultural commodities in India was 777 m3 /cap/yr. In the same period, the average global water footprint of the consumption of agricultural commodities was 1066 m3 /cap/yr. The internal component is responsible for 658 m3 /cap/yr and the external component for 119 m3 /cap/yr. Furthermore, the blue component came to 227 m3 /cap/yr, the green component to 459 m3 /cap/yr and the gray component to 92 m3 /cap/yr. The data that is used and generated in this study are rough and in some cases not complete due to the large scale of the study areas. But, a significant relation is visible between high water footprints and poor agricultural practice in the Indian states. The states Chhattisgarh and Orissa have the highest water footprint, which is mainly because of the low water productivity in the local rice production. From the perspective of consumption, the water scarcity is the highest in the Rajasthan, Punjab, Uttar Pradesh, Tamil Nadu and Haryana. This means that the water resources of these states are closest to be exhausted in case of food self sufficiency. Because most of these states are also net exporters of virtual water, the water scarcity from a production perspective is even higher in these states. Since most of the utilizable water supply in India is used for crop production (Hoekstra & Chapagain, 2007), an important criterion for the evaluation of a possible food supply strategy is the pressure on renewable water resources.

"The largest green water footprints can be found in Uttar Pradesh (88 Gm3), Maharashtra (86 Gm3), Karnataka (65 Gm3), Andhra Pradesh (61 Gm3), and Madhya Pradesh (60 Gm3) in India. The largest blue water footprints were found in: Uttar Pradesh (59 Gm3) and Madhya Pradesh (24 Gm3) in India" (Mekonnen and Hoekstra, 2011)

The impact of intermittent irrigations and different nitrogen (N) doses on growth, yield, N use efficiency and water footprints of rice was studied by Kar et al, 2015. In this study, a rice cultivar, 'Lalat' was grown with 3 water regimes in main plots and 5 N levels in subplots (0, 60, 90, 120 and 150 kg N/ha). "Among water management, lowest mean water footprint (WFP) was observed with irrigation after 2 days of water disappearance but it was at par with continuous flooding of 5 cm. Yield, biomass and leaf area also did not significantly differ between these two, but these were significantly lower in irrigation after 5 days of water disappearance. These results suggest irrigation after 2 days of water disappearance can reduce water input without affecting rice yields. On the other hand, water productivity was higher in irrigation after 5 days of water disappearance though grain yield was less under this treatment. Among N treatments, the lowest average WFP of 1277 m3 /t was achieved under 150 kg N /ha which was at par with 120 kg N/ ha but highest WFP of 2532 m3 /t was observed when no N was applied. The reduction of WFP with higher dose of N was attributed to mainly increased grain yield of rice. Similar studies on reducing water consumption with mulching and optimized irrigation scheduling practices, found positive results in form of reduced water consumption followed by increased yield and quality" (Dawar et al. 2023; Vyas and Mishra 2023).

"Moreover, India suffers from green water scarcity" (Schyns et al., 2019). "It is a water stressed country with 1544 m3 of water available per capita. 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 m3 /cap/year" (Hoekstra and Chapagain, 2008).

Verma et al (2009) analyzed "inter-state virtual water flows in India in the context of a large inter-basin transfer plan of the Government as there exists little information on virtual water trade within large countries like India. The analysis shows that the existing pattern of inter-state virtual water trade is worsening scarcities in already water scarce states and that rather than being dictated by water endowments, virtual water flows are influenced by other factors such as per capita gross cropped area and access to secure markets. It was opined that in order to have a comprehensive understanding of virtual water trade, non-water factors of production need to be taken into consideration". Mehla (2022) conducted study to estimate water footprint of major crops of Banas river basin and found out that the water footprint doubled in last decade for major crops of basin such as wheat, bajra, maize, rapeseed and mustard.

The analysis of Benjamin et al (2019) indicates that "between 2005 and 2014, the production of five dominant types of cereal in India increased by 26%. Cereal water footprints have declined due to higher yields for most crops and slightly lower rates of evapotranspiration. There has also been a shift in the area under production, away from the kharif and towards the rabi season, in which total water footprints for all cereals except rice are substantially lower (33.4 to 45.0% compared to kharif), but show a significantly higher dependency on ground and surface water".

The study on the water footprint of food and cooking fuel in rural India conducted by Das et al (2020) revealed that "total WF for cooking, mainly due to the use of fuel wood is twice the WF for food, showing that in the rural areas of India, especially fuel wood is water intensive with large impact on freshwater resources. In rural India, the average WF for food is 800 m3/cap/year. Green water accounts for 57%, blue water for 30% and grey water for 3% of the total WF of food. 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 6m3/cap/year in the north-east to 334m3/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 m3/cap/year) and the blue WF from wheat contributes 87%. The smallest blue WF is in Mizoram (6 m3/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".

Water requirement of sugarcane in Uttar Pradesh, Punjab, Haryana and Bihar is 1400-1600 mm per year while in Maharashtra it is to the tune of 2400-3000 mm for 12 months crop and 3200-3500 for 16-18 months crop. Most of the area under sugarcane is irrigated unscientifically with only 35-45% irrigation efficiency. Increase in crop yield, water saving and water use efficiency have been observed with technological interventions. Ring pit method of planting recoded 96.4% increase in yield followed by skip furrow method of irrigation (38.8%), irrigation at critical growth stages (28.2%) and trash mulching (25.7%). The irrigation water was saved to the tune of 21.7-44.5%. The increase in irrigation water use efficiency was recorded highest with ring pit method of planting (142%) followed by irrigation at critical growth states (85.2%), trash mulching (72.4%) and skip furrow method of irrigation (68.9%). Water footprint of sugarcane irrigated with different IW/CPE ratio was studied and found that it was minimum (141-146 m3/t) with IW/CPE ratio of 0.25 and maximum (188-191 m3/t) with IW/CRP ratio of 1.25 with ratoon crop under silty clay loam and sandy loam soils (Shukla et al, 2020).

"Food loss during production and post-harvest stages of major food crops and animal products in India was studied" by Kashyap and Agarwal (2020). "The study revealed total food loss in harvest and post-harvest stages of the food supply chain for the selected food items to be 58.3 ± 2.22 million tonnes in the year 2013 with the highest losses in sugarcane and rice. The volume of water associated with the food losses was found to be 115 ± 4.15 billion m3, of which 105 ± 3.77 billion m3 was direct water use (blue and green) and 9.54 ± 0.38 billion m3 was indirect water use (grey). Wasted sugarcane and rice were found to be the largest contributors for water loss". Kashyap and Agarwal (2020) Kakad and Pachkor (2021) reviewed water footprint for different industries viz. food industry, agro industry, textile industry, construction industry and steel industry. They found that water footprint assessment can be helpful for sustainable water use for different industrial purpose.

6. Conclusion

World wide studies have been conducted to evaluate the water footprint of different product, services, consumers, nations. The values present are estimated based on the average data for a large area. To get more information on crop wise and site specific studies on water foot print is need to be conducted at local level. Its application will enable site specific crop planning and water management.

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